A Spatial Coding Approach for MIMO Cognitive Radio Networks' Bandwidth Sharing

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Abstract—The existing cognitive network can't work together with licensed (primary) users' network at the same frequency-time domain, and secondary users (SUs) of cognitive network only wait the frequency band occupied by primary users (PUs) to be free. To solve the problem, this paper proposed a spatial coding approach for MIMO cognitive network, where a MIMO base-station with six antennas provides three different spatial codes for three users such as one PU and two SUs, then the SUs can share the bandwidth of PUs. The spatial codes' design for encoding and decoding vectors is provided. Simulation results verify the proposed approach.

Keywords-cognitive radio;MIMO system; spatial coding; bandwidth sharing.

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1. Introduction

To deal with the conflicts between spectrum congestion and under-utilization, cognitive radio (CR) has been recently proposed as a smart and agile technology which allows non-legitimate users to utilize licensed bands opportunistically [1-8]. CR should have the abilities to sense the unemployed spectrum, select the frequency dynamically and control transmitted power. However, the interference caused by sharing the same radio channel becomes an obstacle that limits the whole system performance, such as the system throughput [6]. Thus, another aim of this system should be to maximize the output of the cognitive network without affecting the primary user.

In practical application, cognitive network and primary users' network exist in a same area. Since the bandwidth is originally licensed to the PU, it can be allocated to the SUs when PUs don't occupy the bandwidth, which leads to the usage efficiency of the bandwidth to be very lower. However, if PUs and SUs operating at the same frequency simultaneously, two kinds of interference would be generated inevitably [7,8]. One is the interference from SUs to PU, the other is inversely related. Since the PUs always have a higher priority compared with the SUs in bandwidth usage, the main challenge is to protect PUs from the interference of SUs when SUs operating at the same frequency simultaneously, whereas few solutions about the problem can be found.

The conventional CR scheme had to shut the sub-carrier of the SUs so that the SUs' operation would not interfere with the PUs at the expense of using this victim band. A spatial coding approach for MIMO CR networks is proposed by us to ensure PUs and SUs work at same band-width, and SUs need not to back-off. Applying the proposed approach, the SUs could utilize the victim band for its data transmission, with the condition that the SUs and PUs do not interfere with each other's operation. The proposed spatial coding approach for CR networks introduces IA technique [10-13] so that both PU and SUs can work well in the same frequency simultaneously. The proposed spatial coding technique is only based on linear pre-coding at the transmitters and zero-forcing at the receivers, which requires the channel knowledge to be known exactly [14]. Simulations results verify the proposed approach to be valid.

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2. Mimo CR Downlink Base-band System

In this section, without loss of generality, a MIMO CR downlink base-band system with one base-station (BS) and three mobile stations (MSs) is considered as shown as Fig.1. We assume that the MIMO channel is assumed to be time-varying and the channel coefficients can be acquired by the approach of [14], thus the channel matrix is perfectly known as well.

In Fig.1, the BS transmitter are equipped with 6 antennas and MS receivers are equipped with 2 antennas. The BS transmitter provides three spatial coding flows $\mathbf{v}_i s_i, i=1,2,3$ from is three groups of antennas, each group has two antennas. s_i represents the signal from antenna group i and $\mathbf{v}_i, i=1,2,3$ represents the pre-coding vector at antenna group i , which is a 2×1 vector.

The i^{th} $(1\le i\le 3)$ receiver intended signal along with interference from other BS transmitter antenna group $j(j\ne i)$. The base-band system model in Fig. 1 at a certain time instance can be expressed by

$$\mathbf{r}_i=\mathbf{H}_{ii}\mathbf{v}_i s_i+\sum_{j=1,j\ne i}^{3}\mathbf{H}_{ij}\mathbf{v}_j s_j+\mathbf{n}_i \qquad (1)$$

where $\mathbf{H}_{ij}$ is a 2×2 channel matrix of the link between

MS receiver i and antenna group j, and $\mathbf{H}_{ij}$ is the interfering link between antenna group j and unexpected receiver i. $\mathbf{n}_i$ accounts for the random noise generated in the radio frequency front-end of the receiver i, and $\mathbf{n}_i$ denotes 2×1 additive noise vector, which is assumed to be i.i.d. Gaussian distributed with zero mean and σ^2 variance.

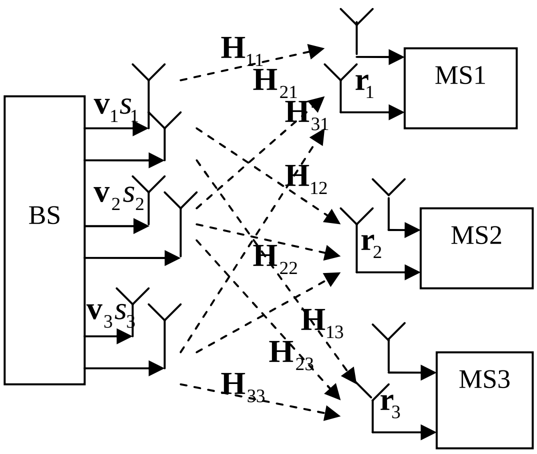

Fig.1 MIMO CR downlink base-band system

The proposed pre-coding vector is a kind of spatial codes, which let multi-users' interference to be cancelled at the receivers.

In other words, BS in Fig. 1 constructs pre-coding vector $\mathbf{v}_i, i=1,2,3$ to encode the transmitting signals $s_i, i=1,2,3$ and decoding vector $\mathbf{u}_i, i=1,2,3$ for MSs to decode the signal at MS receivers.

The intended pre-coding vector $\mathbf{v}_i, i=1,2,3$ and decoding vector $\mathbf{u}_i, i=1,2,3$ should satisfy the following constraints:

$$\mathbf{u}_i^H \mathbf{H}_{ij} \mathbf{v}_i = 0,\ \forall i \neq j \tag{2}$$

$$\text{rank}(\mathbf{u}_i^H \mathbf{H}_{ii} \mathbf{v}_i) = 1 \tag{3}$$

Then, the MS receiver i can acquire its expected signal from BS by multiplying its decode vector $\mathbf{u}_i^H$.

The proposed decoder procedure is simple, the decoded signal $\tilde{y}_i$ at receiver i can be obtain by $\mathbf{u}_i^H \mathbf{r}_i$

$$\begin{aligned} y_i &= \mathbf{u}_i^H \mathbf{r}_i = \mathbf{u}_i^H \mathbf{H}_{ii} \mathbf{v}_i s_i + \sum_{j=1, j\neq i}^{3} \mathbf{u}_i^H \mathbf{H}_{ij} \mathbf{v}_j s_j + \mathbf{u}_i^H \mathbf{n}_i \\ &= c_i s_i + \mathbf{u}_i^H \mathbf{n}_i \end{aligned} \tag{4}$$

where $c_i = \mathbf{u}_i^H \mathbf{H}_{ii} \mathbf{v}_i$, which can determine the BER performance of the receiver i.

Now, we construct the pre-coding vector $\mathbf{v}_i, i=1,2,3$, which need to satisfy the conditions (2) and (3).

Due to (2), we have

$$\left.\begin{aligned} \mathbf{H}_{12}\mathbf{v}_2 - \mathbf{H}_{13}\mathbf{v}_3 = \mathbf{0}_2 \\ \mathbf{H}_{21}\mathbf{v}_1 - \mathbf{H}_{23}\mathbf{v}_3 = \mathbf{0}_2 \\ \mathbf{H}_{31}\mathbf{v}_1 - \mathbf{H}_{32}\mathbf{v}_2 = \mathbf{0}_2 \end{aligned}\right\} \Rightarrow \left\{\begin{aligned} \mathbf{v}_2 = \mathbf{H}_{12}^{-1}\mathbf{H}_{13}\mathbf{v}_3 \\ \mathbf{v}_3 = \mathbf{H}_{23}^{-1}\mathbf{H}_{21}\mathbf{v}_1 \\ \mathbf{v}_1 = \mathbf{H}_{31}^{-1}\mathbf{H}_{32}\mathbf{v}_2 \end{aligned}\right. \tag{5}$$

Then the $\mathbf{v}_1$ will be given through

$$\mathbf{v}_1 = \mathbf{H}_{31}^{-1}\mathbf{H}_{32}\mathbf{H}_{12}^{-1}\mathbf{H}_{13}\mathbf{H}_{23}^{-1}\mathbf{H}_{21}\mathbf{v}_1 \tag{6}$$

From (6), $\mathbf{v}_1$ is the eigenvector of $\mathbf{H}_{31}^{-1}\mathbf{H}_{32}\mathbf{H}_{12}^{-1}\mathbf{H}_{13}\mathbf{H}_{23}^{-1}\mathbf{H}_{21}$. BS can solve $\mathbf{v}_1$ from (6).

Substitute $\mathbf{v}_1$ into (5), we can obtain $\mathbf{v}_3$

$$\mathbf{v}_3 = \mathbf{H}_{23}^{-1}\mathbf{H}_{21}\mathbf{v}_1 \tag{7}$$

and from (5) further obtain $\mathbf{v}_2$

$$\mathbf{v}_2 = \mathbf{H}_{12}^{-1}\mathbf{H}_{13}\mathbf{v}_3 \tag{8}$$

Then substitute $\mathbf{v}_i, i=1,2,3$ into (2) so as to solve the decoding vector $\mathbf{u}_i, i=1,2,3$, which is a 2×1 vector.

$$\left.\begin{aligned} \mathbf{u}_1^H \mathbf{H}_{12}\mathbf{v}_2 = \mathbf{u}_1^H \mathbf{H}_{13}\mathbf{v}_3 = 0 \\ \mathbf{u}_2^H \mathbf{H}_{21}\mathbf{v}_1 = \mathbf{u}_2^H \mathbf{H}_{23}\mathbf{v}_3 = 0 \\ \mathbf{u}_3^H \mathbf{H}_{31}\mathbf{v}_1 = \mathbf{u}_3^H \mathbf{H}_{32}\mathbf{v}_2 = 0 \end{aligned}\right\} \tag{9}$$

In the proposed approach, BS with six antennas uses three pre-coding vectors $\mathbf{v}_i, i=1,2,3$ to provide three independent spatial channels for three MSs (PU and SUs), which means that one PU MS can share its bandwidth with two SU MSs. Here, the pre-coding vectors $\mathbf{v}_i, i=1,2,3$ and decoding vectors $\mathbf{u}_i, i=1,2,3$ are the proposed spatial codes.

Now, we study whether the pre-coding vectors $\mathbf{v}_i, i=1,2,3$ and decoding vectors $\mathbf{u}_i, i=1,2,3$ can be used in MIMO CR uplink base-band system.

3. Mimo CR Uplink Base-band System

Similar to the MIMO CR downlink base-band system in Fig.1, a MIMO CR uplink base-band system with one base-station (BS) and three mobile stations (MSs) is considered as shown as Fig.2.

The MS transmitters provide three spatial coding flows $\mathbf{v}_i s_i, i=1,2,3$ from their antennas, s_i represents the signal from MS i and $\mathbf{v}_i, i=1,2,3$ represents the pre-coding vector at MS i, which is a 2×1 vector. BS divides its six antennas into three groups: group i^{th} $(1\le i\le 3)$, each group has two antennas.

The received signal of the BS group i^{th} $(1\le i\le 3)$ has the interference from other MS $j(j\neq i)$. The base-band system model in Fig. 2 at a certain time instance is expressed by

$$\mathbf{r}_i = \mathbf{G}_{ii}\mathbf{v}_i s_i + \sum_{j=1, j\neq i}^{3} \mathbf{G}_{ij}\mathbf{v}_j s_j + \mathbf{n}_i \tag{10}$$

where $\mathbf{G}_{ij}$ is a 2×2 channel matrix of the link between antenna group i and the transmitter of MS j, and $\mathbf{G}_{ij}$ is the interfering link between antenna group i and unexpected transmitter j. $\mathbf{n}_i$ accounts for the random noise generated in the radio frequency front-end of the BS receiver of antenna group i, and $\mathbf{n}_i$ denotes 2×1 additive noise vector, which is assumed to be i.i.d. Gaussian distributed with zero mean and σ^2 variance.

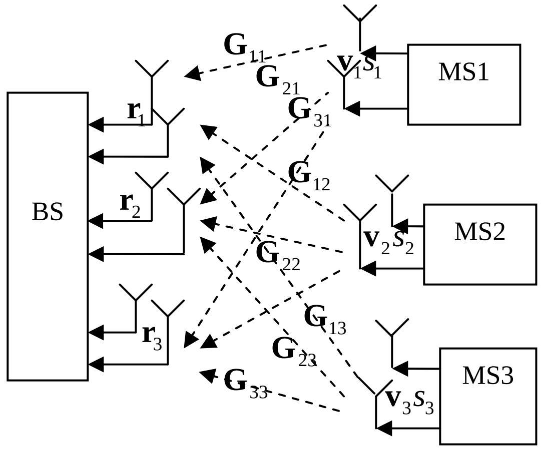

Fig.2 MIMO CR uplink base-band system

If the band-width of downlink and uplink of the CR network are same, the channel matrix $\mathbf{G}_{ij}\approx\mathbf{H}_{ij}$, MSs can use the pre-coding vectors $\mathbf{v}_i, i=1,2,3$ in downlink system, else needs to repeat the algorithms in Section II to re-construct $\mathbf{v}_i, i=1,2,3$.

MSs in Fig. 2 construct pre-coding vector $\mathbf{v}_i, i=1,2,3$ to encode the transmitting signals $s_i, i=1,2,3$ and decoding vector $\mathbf{u}_i, i=1,2,3$ for BS to decode the signal at BS receivers.

The intended MS pre-coding vector $\mathbf{v}_i, i=1,2,3$ and BS decoding vector $\mathbf{u}_i, i=1,2,3$ should satisfy the following constraints:

$$\mathbf{u}_i^H\mathbf{G}_{ij}\mathbf{v}_i=0,\ \ \forall i\neq j \qquad (11)$$

$$\mathrm{rank}(\mathbf{u}_i^H\mathbf{G}_{ii}\mathbf{v}_i)=1 \qquad (12)$$

Then, the BS receiver antenna group i can acquire its expected signal from BS by multiplying its decode vector $\mathbf{u}_i^H$.

The proposed BS decoder procedure is simple, the decoded signal $\tilde{y}_i$ at BS receiver i can be obtain by $\mathbf{u}_i^H\mathbf{r}_i$,

$$y_i=\mathbf{u}_i^H\mathbf{r}_i=\mathbf{u}_i^H\mathbf{G}_{ii}\mathbf{v}_i s_i+\sum_{j=1,j\neq i}^{3}\mathbf{u}_i^H\mathbf{G}_{ij}\mathbf{v}_j s_j+\mathbf{u}_i^H\mathbf{n}_i$$
$$=d_i s_i+\mathbf{u}_i^H\mathbf{n}_i \qquad (13)$$

where $d_i=\mathbf{u}_i^H\mathbf{G}_{ii}\mathbf{v}_i$.

The $\mathbf{v}_1$ will be given through

$$\mathbf{v}_1=\mathbf{G}_{31}^{-1}\mathbf{G}_{32}\mathbf{G}_{12}^{-1}\mathbf{G}_{13}\mathbf{G}_{23}^{-1}\mathbf{G}_{21}\mathbf{v}_1 \qquad (14)$$

From (14), $\mathbf{v}_1$ is the eigenvector of $\mathbf{G}_{31}^{-1}\mathbf{G}_{32}\mathbf{G}_{12}^{-1}\mathbf{G}_{13}\mathbf{G}_{23}^{-1}\mathbf{G}_{21}$. $\mathbf{v}_1$ can be solved from (14).

Similar to (7) and (8), MSs can obtain $\mathbf{v}_3$ and $\mathbf{v}_2$

$$\mathbf{v}_3=\mathbf{G}_{23}^{-1}\mathbf{G}_{21}\mathbf{v}_1 \qquad (15)$$

$$\mathbf{v}_2=\mathbf{G}_{12}^{-1}\mathbf{G}_{13}\mathbf{v}_3 \qquad (16)$$

Similar to (9), MSs obtain the decoding vector $\mathbf{u}_i, i=1,2,3$, which is a 2×1 vector.

$$\left.\begin{aligned}\mathbf{u}_1^H\mathbf{G}_{12}\mathbf{v}_2=\mathbf{u}_1^H\mathbf{G}_{13}\mathbf{v}_3=0\\ \mathbf{u}_2^H\mathbf{G}_{21}\mathbf{v}_1=\mathbf{u}_2^H\mathbf{G}_{23}\mathbf{v}_3=0\\ \mathbf{u}_3^H\mathbf{G}_{31}\mathbf{v}_1=\mathbf{u}_3^H\mathbf{G}_{32}\mathbf{v}_2=0\end{aligned}\right\} \qquad (17)$$

In practical application, it is difficult for MSs with lower complexity to complete the construction of spatial codes $\mathbf{v}_i, i=1,2,3$ and $\mathbf{u}_i, i=1,2,3$, such as the calculation of (14) and obtaining the parameters of the matrices in (14). We can resort to the approach in [14] to move the computation complexity of the spatial codes to BS, BS estimates the parameters of the matrices in (14), calculate (14) and all spatial codes $\mathbf{v}_i, i=1,2,3$ and $\mathbf{u}_i, i=1,2,3$.

4. Results of Simulation

In this section, our attention will focus on the MIMO CR downlink base-band system with three MSs, namely one primary user (MS1 in Fig.1) and two secondary users SU1(MS2 in Fig.1) and SU2(MS3 in Fig.1). A specific example will illustrate the performance of our spatial coding approach. We check whether the proposed approach can ensure PUs and SUs to share the band-width, and SUs need not back-off. In Fig.1, the three original signal sequences at each group of antennas are transmitted to their corresponding receivers.

The parameters of channel matrices in (1) and Fig. 1 are assumed to be generated randomly,

$$H_{11}=\begin{bmatrix}0.9554 & 0.1548\\ 0.1332 & 0.8677\end{bmatrix}, H_{12}=\begin{bmatrix}0.2501 & 0.0686\\ 0.3277 & 0.2994\end{bmatrix},$$
$$H_{13}=\begin{bmatrix}0.5916 & 0.2359\\ 0.2033 & 0.3984\end{bmatrix}, H_{21}=\begin{bmatrix}0.5017 & 0.7960\\ 0.6508 & 0.2334\end{bmatrix},$$

$$H_{22}=\begin{bmatrix}0.6008 & 0.5158\\ 0.1125 & 0.8378\end{bmatrix},\ H_{23}=\begin{bmatrix}0.2208 & 0.2776\\ 0.4982 & 0.6525\end{bmatrix},$$
$$H_{31}=\begin{bmatrix}0.3173 & 0.2742\\ 0.5098 & 0.1973\end{bmatrix},\ H_{32}=\begin{bmatrix}0.1112 & 0.3964\\ 0.2974 & 0.4208\end{bmatrix},$$
$$H_{33}=\begin{bmatrix}0.6115 & 0.0919\\ 0.6938 & 0.7021\end{bmatrix}.$$

With (6)-(8), BS calculate the encoding vector v_i, and the encoding matrix is as follows,

$v_1 = \begin{bmatrix} 0.9519 \\ -0.3065 \end{bmatrix}$, $v_2 = \begin{bmatrix} 0.8300 \\ 0.1905 \end{bmatrix}$, $v_3 = \begin{bmatrix} 0.0548 \\ 0.7979 \end{bmatrix}$.

Similarly, the decoding vector u_i can be solved by using (9), $u_1 = \begin{bmatrix} 0.3290 \\ -0.2207 \end{bmatrix}$, $u_2 = \begin{bmatrix} 0.5480 \\ -0.2336 \end{bmatrix}$, $u_3 = \begin{bmatrix} -0.4248 \\ 0.2180 \end{bmatrix}$.

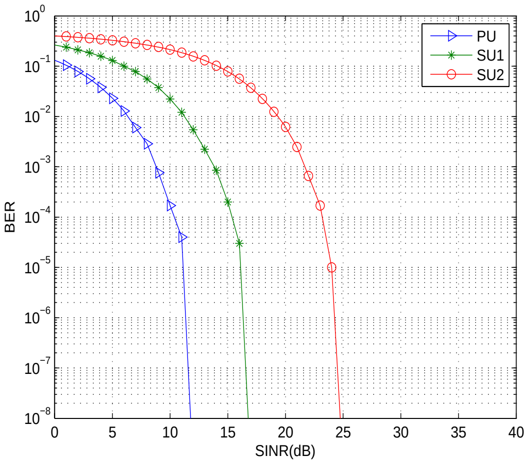

Fig.3 the BER curve of each user

Then BS sends the decoding vector to its corresponding receiver through control channel so that each MS receiver just uses (13) to separate the desired signal from interferers.

Fig.3 shows the BER curve of each MS user.

In the simulation, we have $c_1 = \mathbf{u}_1^H \mathbf{H}_{11} \mathbf{v}_1 = 0.3143$, $c_2 = \mathbf{u}_2^H \mathbf{H}_{22} \mathbf{v}_2 = 0.2680$, and $c_3 = \mathbf{u}_3^H \mathbf{H}_{33} \mathbf{v}_3 = 0.0850$, $c_1 > c_2 > c_3$.

From Fig.3 we can see that the BER of PU is best due to $c_1 > c_2 > c_3$, when SNR=12dB, the PU's BER <10^{-7}.

SU1 and SU2 can share the band-width with PU, their BERs are smaller than 10^{-7}, when SNRs are larger than 18dB and 26dB, respectively, which are determined by c_2 and c_3.

5. Conclusions

This paper develops a spatial coding approach for MIMO cognitive radio network. Limited the paper size, we only consider the approach to be applied in 2×2 MIMO perfect channel. Because the network has cognitive competence, we assume the spatial channels to be known perfectly. Compared with the conventional MIMO CR system, this proposed system keeps PUs and SUs to share the same band-width at the same time, which reduces the implementation complexity of MS receivers. This paper provides the algorithms to construct the encoding and decoding vectors from downlink channel and uplink channels. Different from the IA technique [10-13], the paper simplified the spatial coding process MIMO base-station and PU and SU receivers, and there is no requirement for PU and SU MSs to be linked by Internet and joint decoding. PU and SU receivers can independently use simple spatial codes to separate the desired signal from interferers other than collaborative decoding, which makes the proposed spatial coding process practical.

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