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Research Article

Game-Theoretic Beamforming and Power Allocation in MIMO Cognitive Radio Systems with Transmitter Antenna Correlation

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Multi-input multioutput (MIMO) technique provides a promising solution to enhance the performance of wireless communication systems. In this paper, we consider antenna correlation at the transmitter in practical cognitive MIMO systems. What is more, a game-theoretic framework is conducted to analyze the optimum beamforming and power allocation such that each user maximizes its own rate selfishly under the transmitting power constraint and the primary user (PU) interference constraint. The design of the cognitive MIMO system is formulated as a noncooperative game, where the secondary users (SUs) compete with each other over the resources made available by the PUs. Interestingly, as the correlation parameter grows, the utility degrades. Nash equilibrium is considered as the solution of this game. Simulation results show that the proposed algorithm can converge quickly and clearly outperforms the strategy without game.

1. Introduction

The explosive expansion in wireless communications over the past several years has given rise to severe technical challenges which include the demand of transmitting multimedia date at high rates in an environment rich in scattering. Cognitive radio (CR), which is proposed in 1999 [1], is envisaged as an efficient way to enhance the spectrum utilization [2]. In CR networks, secondary users (SUs) are allowed to access the licensed spectrum only if the interference caused by SUs at primary users (PUs) is kept below a given threshold. Multi-input multioutput (MIMO) technique is an important recent development in wireless communications due to their potential in meeting the challenges caused by fading channels as well as power and bandwidth limitations. It is thus quite natural to combine the MIMO and the cognitive radio techniques to achieve higher spectral efficiency. This technological combination results in the so-called cognitive MIMO radio [3].

Joint power allocation and beamforming, as an effective interference suppression technology, has been widely used in multiple antenna systems [4–7]. In [4], aiming at maximizing the capacity of cognitive systems while satisfying the quality of service (QoS) of PUs, Zhang et al. considered SIMO-MAC for the CR network and proposed a ZF-DFE algorithm at the cognitive base station. Meanwhile, for the SINR fairness issue, the MMSE receiving scheme is proposed to transform the multiconstraint optimization problem into multiple single constraints. In [5], power allocation and beamforming techniques were introduced to CR systems, where SUs cooperated with PUs under different constraints. It proposed a new iterative algorithm and found an optimum solution by the principle of duality transformation model finally. In [6], the authors studied MIMO two-way relaying channels, in order to maximize the sum rate. A joint beamforming and power allocation scheme was proposed for all nodes in the network, subject to a total network power constraint. Aiming at improving the energy and spectral efficiency of MIMO dynamic spectrum networks, the authors in [7] used game theory, variational inequalities theory, and recession analysis, to jointly optimize the beamformers, power, and spectrum allocation for each link to minimize the total transmitting power subject to rate demands. However, all of the algorithms described in [4–7] cannot be applied directly for practical systems, since independent, identically distributed (i.i.d.)

channel was assumed to be known at the cognitive base station.

However, in many practical situations, the rich scattering environment does not always exist and channel fading correlation may exist, which means that channel capacity degrades greatly under fading correlation [8, 9]. This has given an impetus for studying MIMO systems in correlated fading environments. Toward this end, some recent papers [10, 11] have studied its effect on the capacity of multielement antenna and [12] have shown the loss of the spatial degrees of freedom (DOF) due to antenna correlation. However, to the best of our knowledge, no studies have been performed to look at this problem in a cognitive MIMO radio environment via game theory.

Game theory, as an important branch of mathematical theories, was proposed by Goodman and Mandayam for the first time to be used in wireless systems for power control [13]. The authors in [14] proposed a joint beamforming and power allocation algorithm based on game theory. The objective is to maximize the sum rate of SUs subject to the transmitting power constraint and the PU interference constraint. The extension to the cognitive MIMO system is also considered [15–17]. It is worth mentioning that all of these works are based on i.i.d. channels. However, it is difficult to obtain i.i.d. channels in practice. Hence, in [18], with consideration of antenna correlation, a power allocation game for uplink MIMO access channels was provided to maximize the mutual information rate under power constraint.

Inspired by the above preceding works, with consideration of antenna correlation, this paper addresses the joint optimization of beamforming and power allocation in cognitive MIMO systems. By utilizing the Kronecker propagation model [19], considering the transmitter antenna correlation, a new interference constraint condition is obtained. A new cost function is proposed to enable rapid convergence of the joint power allocation and beamforming algorithm. Also, the existence of NE is proved.

The rest of this paper is structured as follows. We first provide the system model used to represent the fading MIMO downlink channel with antenna correlation and formulates the throughput optimization problem under the interference constraint of PU. In Section 3, under the game theoretical framework, we propose a joint power allocation and beamforming algorithm with antenna correlation. Numerical simulation results are given in Section 4. Finally, Section 5 concludes this paper.

2. System Model

We consider a cognitive MIMO system as shown in Figure 1, which comprises one secondary base station (SBS), K secondary users SU $1, \dots,$ SU K, and one PU. The SBS is equipped with N_t antennas, while each SU and the PU were equipped with a single antenna.

The signal transmitted from the SBS is represented by

$$\mathbf{X} = \mathbf{FPS}, \quad (1)$$

where $\mathbf{S} = [\mathbf{s}_1, \dots, \mathbf{s}_K]$, $\mathbf{S}$ denotes the transmitted signal vector, in which s_k is the desired signal for secondary user

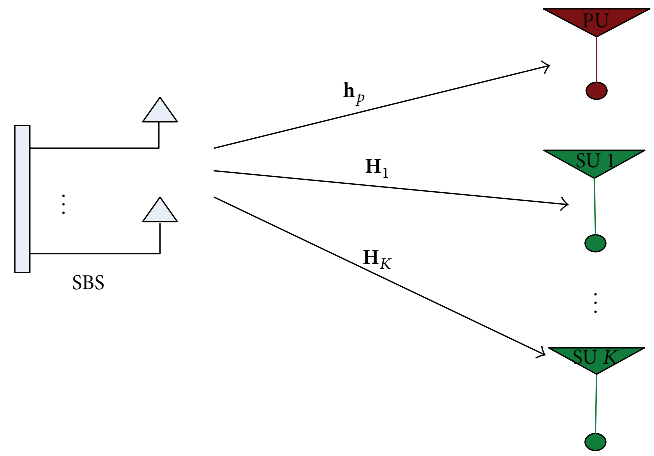

Figure 1: Cognitive MIMO system.

k, and $\mathbf{F} = [\mathbf{f}_1, \mathbf{f}_2, \dots, \mathbf{f}_K]$ denotes the beamforming matrix, with $\mathbf{f}_k$ being an $(M \times K)$ beamforming vector for the kth SU. Likewise, $\mathbf{P} = \operatorname{diag}\{\sqrt{p_1}, \dots, \sqrt{p_K}]$ is the matrix of power allocated for transmitting signals. For simplicity, we assume that all SUs are homogeneous and experience independent fading.

The signal received at the kth SU is given by

$$y_k = \mathbf{H}_k \mathbf{X} + n_k = \sqrt{p_k} \mathbf{H}_k \mathbf{f}_k s_k + \mathbf{H}_k \sum_{i=1, i \neq k}^{k} \sqrt{p_i} \mathbf{f}_i s_i + n_k, \quad (2)$$

where $\mathbf{H}_k \in \mathbb{C}^{1 \times N_t}$ is the channel coefficient from the SBS to the kth SU and n_k is an additive white Gaussian noise with zero mean and variance σ_k^2.

In order to take the antenna correlation effects at the transmitters into account, we will assume the different channel matrices to be structured according to the Kronecker propagation model [20]:

$$\mathbf{H}_k = \mathbf{R}_r^{1/2} \mathbf{H}_w \mathbf{R}_t^{1/2}, \quad (3)$$

where $\mathbf{H}_w$ is a matrix with independent and identically distributed (i.i.d.) complex Gaussian entries with mean zero and variance one and $\mathbf{R}_r$ and $\mathbf{R}_t$ denote antenna correlation matrix at the receiver and the transmitter sides, respectively. Such a model is usually valid when assuming independent transmitting and receiving correlations. In this paper, we only consider the system that operates in a semicorrelated Rayleigh flat-fading environment, which means correlation exists either at the transmitter or at the receiver but not both. Due to the duality between correlation at the transmitter and correlation at the receiver, only the case of correlation at the transmitter is considered in this paper; that is, there is sufficiently rich scattering at the receiver so that the receiving antennas are uncorrelated, so that R_r is an identity matrix.

The signal received at the PU is expressed as

$$y_p = s_p + \mathbf{h}_p \sum_{i}^{k} \sqrt{p_i} \mathbf{f}_i s_i + n_p, \quad (4)$$

where $\mathbf{h}_p \in \mathbb{C}^{1\times N_t}$ is the channel coefficient from the SBS to the PU, s_p is the signal from the PU transmitter, with zero mean, and variance $\sqrt{P_p}$, and n_p is an additive white Gaussian noise with zero mean and variance σ_p^2.

The signal-to-interference-plus-noise ratio (SINR) at the kth SU is represented by

$$\mathrm{SINR}_k = \frac{p_k \left|\mathbf{H}_k \mathbf{f}_k\right|^2}{\left|\mathbf{H}_k\right|^2 \sum_{i=1,i\neq k}^{K} p_i \left|\mathbf{f}_i\right|^2 + \sigma_k^2}. \tag{5}$$

The SINR at the PU is represented by

$$\mathrm{SINR}_p = \frac{p_p}{\sum_{i=1}^{K} p_i \left|\mathbf{h}_p \mathbf{f}_i\right|^2 + \sigma_p^2}. \tag{6}$$

In order to ensure the quality of service (QoS) of SUs, SINR of each SU should be above threshold γ_k; that is,

$$\mathrm{SINR}_k \geq \gamma_k. \tag{7}$$

On the other hand, to ensure QoS of the PU, the interference perceived at the PU should be no greater than a threshold I_{th}; that is,

$$\sum_{k=1}^{K} p_k \left|\mathbf{h}_p \mathbf{f}_k\right|^2 \leq I_{\mathrm{th}}. \tag{8}$$

3. Noncooperative Game Formulation

Game theory is an effective tool to analyze competitive optimization problems. In cognitive MIMO systems, each SU's transmission is a source of interference for the others. Each SU is rational and selfish, with a desire to choose a strategy maximizing its own utility, without consideration of interference to other users. Based on the system model described above, a noncooperative game can be formulated by

$$G = \left\{\Omega, \left\{\mathbf{f}_k, p_k\right\}_{k\in\Omega}, \left\{u_k\right\}_{k\in\Omega}\right\} \tag{9}$$

and the players in this game are the secondary users. The game strategies of the players are the beamforming weights and transmitting power (denoted by $\mathbf{f}_k$ and p_k for secondary user k), which is nonnegative. The utility for each player is the profit (i.e., revenue minus cost) of SU (denoted by u_k) in sharing the spectrum with the PU and other SUs. SINR can be taken as the optimization variable. Consequently, the utility function can be designed based on the mutual information

$$u_k = \log_2\left(1 + \mathrm{SINR}_k\right). \tag{10}$$

Due to greediness, a payoff function based on (10) leads to an inefficient outcome; that is, each player focuses on the increase of its own utility without nulling the interference to the PU. Pricing has been used as an effective tool to optimize noncooperative game with limited resource in order to prevent the selfish behavior above. Therefore, the payoff function should consist of revenue and cost. Specifically, the new utility function of the kth SU with pricing is rewritten as follows:

$$u_k = \log_2\left(1 + \mathrm{SINR}_k\right) - \lambda p_k \left|\mathbf{h}_p \mathbf{f}_k\right|^2. \tag{11}$$

A noncooperative game problem can be represented by

$$\begin{aligned} \max \quad & \sum_{k=1}^{K} u_k, \quad \forall k \in \Omega \\ \text{s.t.} \quad & \sum_{k=1}^{k} p_k \left|\mathbf{h}_p \mathbf{f}_k\right|^2 \leq I_{\mathrm{th}} \\ & \sum_{k=1}^{k} p_k \leq p_T \\ & \mathrm{SINR}_k \geq \gamma_{\min,k}, \end{aligned} \tag{12}$$

where p_k and $\mathbf{f}_k$ are the set of strategies space of the kth SU and p_T is power budget of the SBS. Hence, under the condition of satisfying the above three constraints, each SU can select optimal transmitting power and beamforming vector by competing with other SUs to maximize its own utility. The first constraint limits the interference to PUs, the secondary constraint satisfies transmission power allocation of SBS, and the last one ensures QoS of SUs.

3.1. Existence of Nash Equilibrium. To analyze the outcome of the game, the achievement of a Nash equilibrium is a well-known optimality criterion. In a Nash equilibrium point, every player is unilaterally optimal and no player can increase its utility alone by changing its own strategy [21]. According to the fundamental game theory result, if the following conditions are satisfied, the strategic noncooperative game admits at least one Nash equilibrium point.

(a) The set of strategies is a closed bounded convex set.

(b) The utility function is continuous quasiconcave on action space and has increasing differences.

Next, whether the proposed utility function satisfies these two conditions is verified. It is obvious that it satisfies the first condition because p_k and $\mathbf{f}_k$ are limited. So, we only tested the scheme to satisfy the second condition. By finding the second derivative of $u_k(\cdot)$with respect to power and beamforming, respectively, we get

$$\begin{aligned} &\frac{\partial^2 u_k}{\partial p_k^2} \\ &\quad = -\frac{1}{In_2} \frac{\left|\mathbf{H}_k \mathbf{f}_k\right|^4}{\left(p_k \left|\mathbf{H}_k \mathbf{f}_k\right|^2 + \left|\mathbf{H}_k\right|^2 \sum_{i=1,i\neq k}^{K} p_i \left|\mathbf{f}_i\right|^2 + \sigma_k^2\right)}, \end{aligned} \tag{13}$$

$$\begin{aligned} &\frac{\partial^2 u_k}{\partial \left[\left|\mathbf{f}_k\right|^2\right]^2} \\ &\quad = -\frac{1}{In_2} \frac{p_k^2 \left|\mathbf{H}_k\right|^4}{\left(p_k \left|\mathbf{H}_k \mathbf{f}_k\right|^2 + \left|\mathbf{H}_k\right|^2 \sum_{i=1,i\neq k}^{K} p_i \left|\mathbf{f}_i\right|^2 + \sigma_k^2\right)^2}. \end{aligned} \tag{14}$$

It is easy to check that $\partial^2 u_k/\partial p_k^2 \le 0$ and $\partial^2 u_k/\partial[|\mathbf{f}_k|^2]^2 \le 0$, which implies the utility function is convex. Consequently, these utility functions satisfy all the required conditions for the existence of at least one Nash equilibrium based on the noncooperative game with pricing scheme.

3.1.1. Noncooperative Beamforming Game (NBG). In this game, the power of users is fixed, and individual users adjust only their beamforming in their corresponding strategy spaces in order to maximize their corresponding cost function. The NBG is formally defined as

$$\mathrm{NBG} = \left\{\Omega, \{\mathbf{f}_k\}_{k\in\Omega}, \{u_k\}_{k\in\Omega}\right\}, \tag{15}$$

where $\Omega = \{1, 2, \ldots, K\}$ are the secondary users. The game strategy of the players is the beamforming weights (denoted by $\mathbf{f}_k$ for secondary user k), which is nonnegative. u_k is the utility function. In this game, the secondary users maximize their utility function by adjusting their respective beamforming vectors:

$$\begin{aligned} \min \quad & u_k\left(p_k, \mathbf{f}_k\right)_{p_k=\text{fixed}} \\ \text{s.t.} \quad & \mathbf{f}_k^T \mathbf{f}_k = 1. \end{aligned} \tag{16}$$

In order to solve this problem we have the kth user Lagrangian function

$$L_k^{\mathbf{f}_k}\left(\mathbf{f}_k, \alpha_k\right) = u_k + \alpha_k\left(\mathbf{f}_k^T \mathbf{f}_k - 1\right), \tag{17}$$

where α_k is the Lagrange multiplier associated with the constraints on the norm of $\mathbf{f}_k$ in (14).

The necessary conditions for minimizing the Lagrangian in (15) are obtained by differentiating with respect to α_k and $\mathbf{f}_k$ and equating the corresponding partial derivatives to zero

$$\begin{aligned} &\frac{\partial L_k^{\mathbf{f}_k}\left(\mathbf{f}_k, \alpha_k\right)}{\partial \mathbf{f}_k} = 0 \Longrightarrow \\ &\left|\mathbf{f}_k\right|^2 \\ &\quad = \frac{p_k\left|\mathbf{H}_k\right|^2 / In_2\left(\lambda p_k\left|\mathbf{h}_p\right|^2 - \alpha_k\right) - \left|\mathbf{H}_k\right|^2 \sum_{i=1,i\neq k}^K p_i\left|\mathbf{f}_i\right|^2 - \sigma_k^2}{p_k\left|\mathbf{H}_k\right|^2}. \end{aligned} \tag{18}$$

In order to investigate whether Nash equilibrium is optimal, we need to expand the Lagrangian function in Taylor series around the point satisfying the necessary KKT. In this expansion, the term containing the first derivative disappears since the derivative is equal to zero due to the KKT condition, and the higher order terms are neglected. So we only need to determine whether second derivative satisfies the KKT conditions. For the Lagrangian expression in (15) the second-order term in the Taylor expansion is

$$\begin{aligned} D_k^{\mathbf{f}_k} &= (-1)\begin{vmatrix} \dfrac{\partial^2 L_k^{\mathbf{f}_k}\left(\mathbf{f}_k, \alpha_k\right)}{\partial \mathbf{f}_k^2} & \dfrac{\partial^2 L_k^{\mathbf{f}_k}\left(\mathbf{f}_k, \alpha_k\right)}{\partial \mathbf{f}_k \partial \alpha_k} \\ \left(\dfrac{\partial^2 L_k^{\mathbf{f}_k}\left(\mathbf{f}_k, \alpha_k\right)}{\partial \mathbf{f}_k \partial \alpha_k}\right)^T & \dfrac{\partial^2 L_k^{\mathbf{f}_k}\left(\mathbf{f}_k, \alpha_k\right)}{\partial \alpha_k^2} \end{vmatrix} = (-1)\begin{vmatrix} \dfrac{1}{In_2}\dfrac{2p_k\left|\mathbf{H}_k\right|^2\left(v_k\right)^2 - 4\left(p_k\mathbf{f}_k\left|\mathbf{H}_k\right|^2\right)^2}{\left(v_k\right)^2} - 2\lambda p_k\left|\mathbf{h}_p\right|^2 + 2\alpha_k & 2\mathbf{f}_k \\ 2\mathbf{f}_k^T & 0 \end{vmatrix} \\ &= 4 > 0, \end{aligned} \tag{19}$$

where $v_k = p_k|\mathbf{H}_k\mathbf{f}_k|^2 + |\mathbf{H}_k|^2\sum_{i=1,i\neq k}^K p_i|\mathbf{f}_i|^2 + \sigma_k^2$.

Thus, a Nash equilibrium point of the NBG is satisfied. It is an optimal equilibrium point with respect to the constrained maximization of the user utility function.

3.1.2. Noncooperative Power Control Game (NPG). In this game, the power of user is fixed, and individual users adjust only their beamforming in their corresponding strategy spaces in order to maximize their corresponding utility function. The NPG is formally defined as

$$\mathrm{NPG} = \left\{\Omega, \{p_k\}_{k\in\Omega}, \{u_k\}_{k\in\Omega}\right\}, \tag{20}$$

where $\Omega = \{1, 2, \ldots, K\}$ are the secondary users. The game strategy of the players is the power allocation weights (denoted by p_k for secondary user k), which is nonnegative, and u_k is the utility function. In this game, the secondary users maximize their utility function by adjusting their respective power allocation vectors:

$$\min u_k\left(p_k, \mathbf{f}_k\right)_{f_k=\text{fixed}}. \tag{21}$$

Given a beamforming vector, taking a derivative of the utility function with respect to p_k yields

$$\begin{aligned} \frac{\partial u_k}{\partial p_k} &= \frac{1}{In_2}\frac{\left|\mathbf{H}_k\mathbf{f}_k\right|^2}{p_k\left|\mathbf{H}_k\mathbf{f}_k\right|^2 + \left|\mathbf{H}_k\right|^2\sum_{i=1,i\neq k}^K p_i\left|\mathbf{f}_i\right|^2 + \sigma_k^2} \\ &\quad - \lambda\left|\mathbf{h}_p\mathbf{f}_k\right|^2. \end{aligned} \tag{22}$$

It is straightforward that equation $\partial u_k/\partial p_k = 0$ must hold, in order to maximize utility function. Solving this equation for p_k yields

$$p_k = \frac{\left|\mathbf{H}_k\right|^2 / \lambda In_2\left|\mathbf{h}_p\right|^2 - \left|\mathbf{H}_k\right|^2\sum_{i=1,i\neq k}^K p_i\left|\mathbf{f}_i\right|^2 - \sigma_k^2}{\left|\mathbf{H}_k\mathbf{f}_k\right|^2}. \tag{23}$$

3.1.3. Joint Power Allocation and Beamforming Algorithm. In this section, we present an iterative algorithm that repeats the beamforming and the power allocation steps until it converges [14]. The proposed algorithm consists of two main steps, which correspond to the two subgames NPG and NBG and which are performed sequentially by users in the system. First, the NPG part operates for a certain specified number of iterations N, using some initial beamforming matrix, and computes a power vector which may not be optimal because the algorithm stops without necessarily converging. Then, NPG is used to find the optimal beamforming matrix. This set of power allocation and beamforming steps is repeated, using the power in each round and then the beamforming vectors calculated from the previous round, until convergence is achieved to a locally optimal pair of power and beamforming vectors. The algorithm is proposed so as to maximize the sum rate of SUs, while not degrading QoS for the primary link.

The iterative algorithm is summarized as follows.

Step 1. Set $n := 0$; initialize powers $p_k^{(0)}$ and beamforming vectors $\mathbf{f}_k^{(0)}$, $k \in \Omega$.

Step 2.

At each iteration, set $n_0 := n$, $k \in \Omega$.

Repeat {

$k \in \Omega$.

Set $n := n + 1$.

For each user $k \in \Omega$ update power

$$p_k^{(n+1)} = \frac{\left|\mathbf{H}_k\right|^2 / \lambda I n_2 \left|\mathbf{h}_p\right|^2 - \left|\mathbf{H}_k\right|^2 \sum_{i=1,i\neq k}^{K} p_k^{(n)} \left|\mathbf{f}_k^{(n)}\right|^2 - \sigma_k^2}{\left|\mathbf{H}_k \mathbf{f}_k^{(n)}\right|^2}. \quad (24)$$

Set $n := n + 1$; consider $\mathbf{f}_k^{(n)} := \mathbf{f}_k^{(n-1)}$ for each $k \in \Omega$.

until $n = n_0 + N$}.

Step 3. For each user $k \in \Omega$ update the beamforming vector,

$$\mathbf{f}_k(n+1) = \frac{\mathbf{f}_k(n) + m\beta x_k(n)}{\left\|\mathbf{f}_k(n) + m\beta x_k(n)\right\|}, \quad (25)$$

where $x_k(n)$ is the best response for NBG, $m = \operatorname{sgn}[\mathbf{f}_k^T(n) x_k(n)]$, and β is a parameter that limits how far in terms of Euclidian distance the updated beamforming vector can be from the old beamforming vector.

Step 4. Repeat Steps 1 and 2 until convergence.

4. Simulation Results

In this section, we will illustrate the performance of the proposed algorithm by simulation results. The Matlab tool is used to verify the proposed algorithm. There are one PU, one SBS, and three SUs. The SBS is equipped with four antennas, and PU and each SU are equipped with only one antenna. The background noise power at each user is set to $\sigma^2 = 0.01$ W, the period of block fading is 1 s, the maximum transmission power of SBS is set to $p_T = 10$ W, the PU's transmitting power is set to $p_p = 1$ W, the iterative threshold is set to $\varepsilon = 10^{-3}$, the initial transmission power is $\mathbf{p}(1) = (0.1, 0.1, 0.1)$ W, the beamforming vector is $\mathbf{f}_k$, that is, $\beta = 0$, iterative step is $\beta = 0 : 0.01 : 1$, and the number of power iterations is 20.

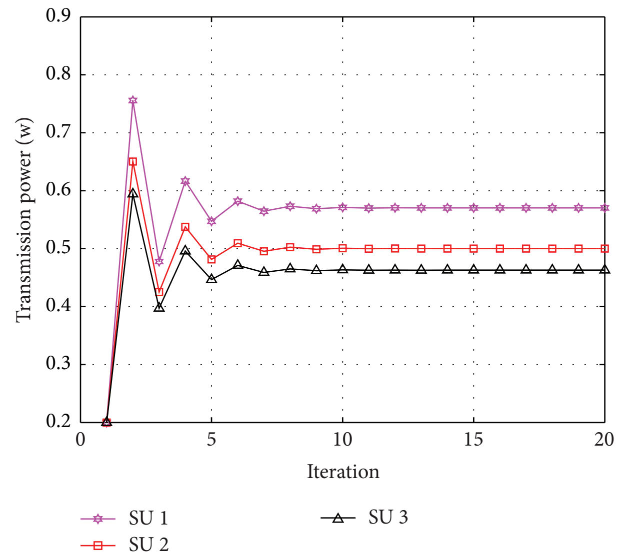

Figure 2: Each SU's transmission power when reaching convergence.

We first simulate and analyze the convergence of joint beamforming and power allocation algorithm with respect to the transmitting power level. As shown in Figure 2, the transmitting power of each secondary link, in which the power initialization for each secondary link is the same as 0.2, converges in a few iterations due to the preceding update of the beamforming vector. After that, the sum utility of secondary users is maximized and the existence of Nash equilibrium point is proven.

Figure 3 depicts one secondary user and different correlation scenarios: $\rho_t = 0.1, 0.5, 0.9$. The figures show that a high correlation had a large impact on the system performance.

In Figure 4, we compare the sum utility of secondary users with/without game theory, from which we can see that the sum utility of secondary users that are processed by game theory is more effective and stable than the one without game.

5. Conclusion

Most of the existing joint beamforming and power allocation algorithms in cognitive MIMO systems only consider i.i.d. channels, which is unlikely to be obtained in practice. Therefore, in this paper, we investigate antenna correlation at the transmitter, so as to adapt to the practical cognitive MIMO system. A joint beamforming and power allocation algorithm based on game theory for a cognitive MIMO system with

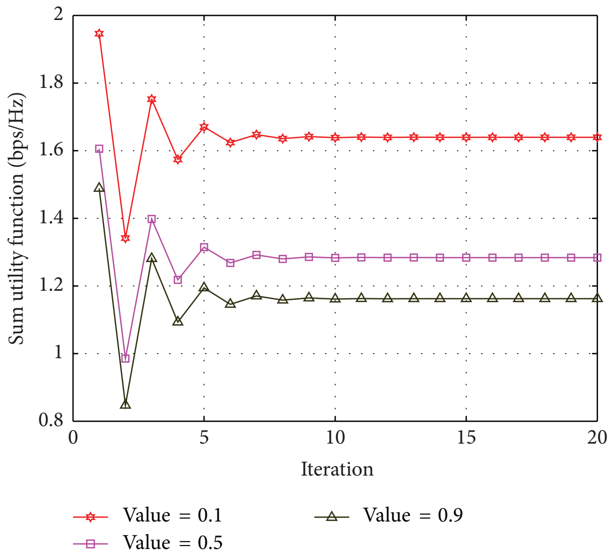

Figure 3: Utility of SUs for different correlation parameters (ρ_t = 0.1, 0.5, 0.9).

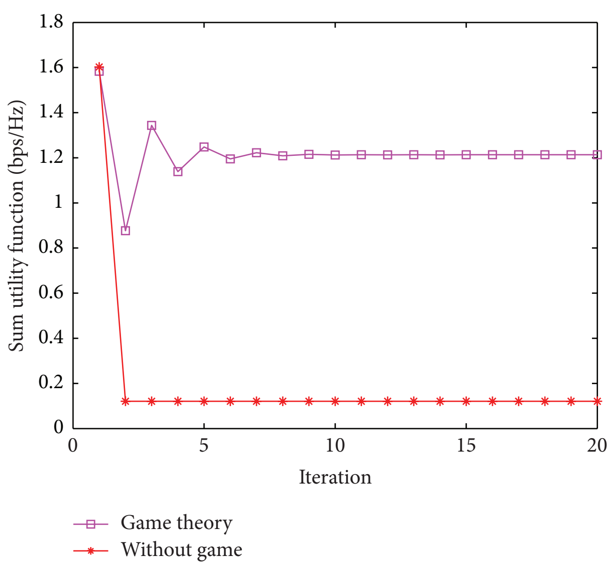

Figure 4: The sum utility of secondary users with/without game theory.

antenna correlation is proposed. The scheme uses an iteration algorithm to guarantee the NE with the antenna correlation effect. Simulation results show that the proposed algorithm clearly outperforms that without game theory.

Conflict of Interests

The authors declare that they have no competing interests.

Acknowledgments

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