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Multiuser-diversity-based interference alignment in cognitive radio networks

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ABSTRACT

As a promising interference management technique, interference alignment (IA) has been applied to cognitive radio (CR) networks. However, the received signal-to-interference-plus-noise ratio (SINR) may decrease dramatically under some channel conditions in IA-based CR networks, and this will reduce the quality of service (QoS) of primary users (PUs). In this paper, we study the problem of SINR decrease and propose a multiuser-diversity-based IA scheme to make it more practical to be applied to CR networks. Since the number of secondary users (SUs) is changing dynamically in practical CR networks, we present two schemes targeted at two different scenarios. In the first scenario with a large number of SUs, the IA network cannot accommodate all the PUs and SUs simultaneously with perfect elimination of interferences. The corresponding scheme is to select those SUs, which can maximally improve the QoS of PUs, to access to the spectrum by forming an IA network with the PUs. Thus the performance of PUs can be significantly improved. To further ensure the interest of SUs, the scheme is revised and a tradeoff is made between the PUs and SUs. In the second scenario with a smaller number of SUs, the IA network can accommodate all the users simultaneously without mutual interference. User selection and antenna selection strategies are adaptively employed to guarantee the performance of PUs. Furthermore, fairness among SUs is also investigated. Simulation results are presented to show the effectiveness of the proposed schemes for CR networks.

1. Introduction

Over the last decade, cognitive radio (CR) has attracted significant attention in solving the spectrum scarcity problem [1–4]. In CR networks, secondary users (SUs) can adaptively choose transmission parameters to access to the licensed spectrum while guaranteeing the quality of service (QoS) of primary users (PUs). Generally, there are two types of spectrum sharing methods, overlay and underlay spectrum sharing [5,6]. In the underlay spectrum sharing, SUs can coexist with PUs, as long as they do not violate the interference temperature limit. However, in practice, the interference temperature limit is difficult to satisfy, and the QoS of PUs could be degraded due to the interference from SUs [7].

Interference alignment (IA) is a recent breakthrough in approaching the capacity of interference networks at high signal-to-noise ratio (SNR) [8], and extensive studies of IA in CR networks have been performed [9–12]. In [13], the idle spectrum is divided into multiple subcarriers, thus the overloaded SUs can be clustered into different groups to form IA. By this means, the sum-rate increase of CR network is achieved. In [14], the spectrum leasing problem is studied with the help of MIMO and IA techniques. By formulating a Stackelberg game, the utilities of primary and secondary users can be enhanced. In [15], the precoding matrix design, frequency clustering, and power allocation are jointly investigated to maximize the spectrum efficiency. The key idea of IA is to consolidate all interference into a certain subspace, so as to reserve the remaining interference-free subspace for the desired signal [16]. In [8], the degrees of freedom (DoFs) and capacity of interference channel using IA were studied, and the closed-form expressions for transmit precoding matrices were presented. However, due to the requirement of global channel state information (CSI), these closed-form expressions are difficult to obtain in practice. Thus, two distinguished iterative algorithms for IA leveraging the reciprocity of wireless networks were designed in [16], named minimum leakage IA (MinIL IA) algorithm and maximal signal to interference plus noise ratio (Max-SINR) algorithm. The Max-SINR performs better than MinIL IA algorithm especially at low and intermediate SNR values due to its larger coherent combining gain (array gain), however its computational complexity is relatively high. In [17], the authors

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proposed an IA scheme based on channel prediction to improve its performance when CSI delay is considered. Due to its promising performance, IA has been rapidly applied to several wireless systems [18–20].

Despite the remarkable performance in solving the interference problem in wireless networks, there are still several hurdles towards the practical implementation of IA [21]. One of them is the SINR degradation problem [16,22–24], which will make the QoS unacceptable. In [16], a Max-SINR algorithm was proposed to achieve the optimal signal to interference plus noise ratio (SINR) of the received signal. In [22], the authors analyzed the origin of this problem, and proposed an antenna switching IA scheme to improve its performance. In [23], a novel IA scheme based on antenna selection was proposed to solve the SINR degradation problem to make it more applicable to CR networks.

Recently, multiuser diversity has been considered in IA to improve its performance [25–28]. Multiuser diversity is a form of inherent diversity in a wireless network, and it is exploited by tracking the channel fluctuations and scheduling transmissions to users when their instantaneous channel quality is near peak [29–31]. In [25], an opportunistic interference aligned user selection scheme was proposed in a multiple-input and multi-output (MIMO) interference channel with three transmitters and more receivers to be selected for each transmitter. An opportunistic IA scheme for the uplink multi-cell environments was designed in [26]. In [27], the authors proposed a new criterion for user selection that can considerably reduce the searching space and the communications overhead between base stations in a two-cell network.

Although some excellent works have been done on multiuser-diversity-based IA, most of them did not consider the specific characteristics of cognitive radio. In this paper, we introduce multiuser-diversity-based IA to CR networks to improve the network's spectrum efficiency. The main contributions are as follows.

(1) The desired signal's SINR degradation is one of the most pressing hurdles that hinder the practical applications of IA. In this paper, by taking advantage of the intrinsic nature of CR networks (e.g., multiple SUs), we propose several algorithms to solve the SINR degradation problem.
(2) Since the number of SUs is changing dynamically in practical CR networks, we present two schemes targeted at two different scenarios. In the first scenario, the number of SUs is greater than the largest number that the IA network can accommodate. The PU's performance can be improved with the help of multiuser diversity brought by the SUs. In the second scenario with a smaller number of SUs, the IA network can accommodate all the users simultaneously. Since no multiuser diversity gain can be achieved in the second scenario, user selection and antenna selection strategies are adaptively exploited to guarantee the QoS of the PU while improving the SU's performance. Specifically, the Max-SINR algorithm is adopted to pursue the solution of IA due to its higher coherent combining gain.
(3) Due to the specific requirements of the CR networks, we propose an algorithm that optimizes PU's performance, and then a hybrid algorithm is presented that can coordinate the priority of PU or SUs to adapt to the different requirements in CR networks. The computational complexity of the algorithms is also analyzed.
(4) Fairness among the SUs is considered to guarantee that each SU can achieve a preferably fair opportunity to access to the spectrum.

The rest of this paper is organized as follows. In Section 2, the system model is presented, and the SINR of desired signals in IA is analyzed. An IA-based spectrum sharing scheme exploiting multiuser diversity in CR networks is presented in Section 3. In Section 4, a scenario with smaller number of SUs is considered. In Section 5, fairness among SUs is taken into account. Simulation results are given and discussed in Section 6. Finally, conclusions are presented in Section 7.

Notation: $\mathbf{I}_d$ represents the $d \times d$ identity matrix. $\mathbf{A}^\dagger$ and $|\mathbf{A}|$ are the conjugate transpose and determinant of matrix $\mathbf{A}$, respectively. $\lambda_{\max}(\mathbf{A})$ means the maximal eigenvalue of the matrix $\mathbf{A}$. $\|\mathbf{a}\|$ and $\mathbf{a}^T$ are the norm and transpose of vector $\mathbf{a}$, respectively. $\mathbb{E}(b)$ indicates the mathematical expectation of b.

2. System description

In this section, we first describe the spectrum sharing problem in CR networks. Then, spectrum sharing based on IA is introduced. Finally, the SINR analysis of the IA-based spectrum sharing is given.

2.1. Spectrum sharing in cognitive radio networks

Two types of spectrum sharing, overlay and underlay, are usually used in CR networks. In the overlay spectrum sharing scenario, based on the results of spectrum sensing [32], SUs can access to the spectrum only when no PUs are occupying it. In the underlay spectrum sharing scenario, SUs can coexist with PUs, as long as PUs' communication is not disturbed. Interference temperature limit is usually used to indicate the tolerable interference level at primary receivers [33]. In this scenario, a SU needs to make a tradeoff between maximizing its own throughput and minimizing the amount of interference it produces at PUs. In this paper, we mainly focus on the underlay spectrum sharing scenario.

Even when the interference temperature limit is followed by SUs strictly, it is still harmful to PUs when there exist unlicensed users occupying the same band with them. Furthermore, the interference among SUs will also inevitably degrade their own performance, and the number of SUs who are granted the opportunity to access to the spectrum is highly confined. Thus, interference management is a big issue in the underlay spectrum sharing of CR networks. In this paper, IA is leveraged to solve this problem.

2.2. Spectrum sharing based on interference alignment

IA can eliminate the interference among users and improve the throughput of wireless networks, and is considered to be used in the underlay spectrum sharing to reduce the interference in this paper.

Consider a K-user MIMO interference channel in CR with a single PU (the 1st user) and $K-1$ SUs (other users) sharing the licensed spectrum.[1] $M^{[k]}$ and $N^{[k]}$ antennas are equipped at the kth transmitter and receiver, respectively. To share the spectrum with the PU, an IA network is formed among PU and SUs. The kth user transmits $d^{[k]}$ data streams. The received signal at the kth receiver can be expressed as

$$\mathbf{y}^{[k]}(n) = \bar{\mathbf{H}}^{[kk]}(n)\mathbf{x}^{[k]}(n) + \sum_{j=1, j\neq k}^{K} \bar{\mathbf{H}}^{[kj]}(n)\mathbf{x}^{[j]}(n) + \mathbf{U}^{[k]\dagger}(n)\mathbf{z}^{[k]}(n), \quad (1)$$

$$\bar{\mathbf{H}}^{[kj]}(n) = \mathbf{U}^{[k]\dagger}(n)\mathbf{H}^{[kj]}(n)\mathbf{V}^{[j]}(n). \quad (2)$$

In (1) and (2), $\mathbf{H}^{[kj]}(n)$ is the $N^{[k]} \times M^{[j]}$ matrix of channel coefficients from the jth transmitter to the kth receiver at the time instant n. Each entity of $\mathbf{H}^{[kj]}(n)$ is independent and identically distributed

[1] The case with more PUs is similar, and can be easily extended.