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Cooperative spectrum sharing of multiple primary users and multiple secondary users☆

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ABSTRACT

This paper proposes a multiple-input multiple-output (MIMO) based cooperative dynamic spectrum access (DSA) framework that enables multiple primary users (PUs) and multiple secondary users (SUs) to cooperate in spectrum sharing. By exploiting MIMO in cooperative DSA, SUs can relay the primary traffic and send their own data at the same time, which greatly improves the performance of both PUs and SUs when compared to the non-MIMO time-division spectrum sharing schemes. Especially, we focus on the relay selection optimization problem among multiple PUs and multiple SUs. The network-wide cooperation and competition are formulated as a bargaining game, and an algorithm is developed to derive the optimal PU-SU relay assignment and resource allocation. Evaluation results show that both primary and secondary users achieve significant utility gains with the proposed framework, which gives all of them incentive for cooperation.

1. Introduction

With advances in cognitive radio (CR) technology, dynamic spectrum access (DSA) is being considered as a promising paradigm to increase spectrum utilization by allowing unlicensed secondary users (SUs) to access and share the licensed spectrum bands of primary users (PUs). Recently, a new model in which PUs and SUs cooperate for data transmissions and spectrum sharing, termed cooperative DSA, attracts research attention [1,2,16]. Time-division channel sharing schemes [2,3] have been proposed to facilitate the PU-SU's cooperative spectrum sharing, in which a PU selects some SUs to cooperatively relay its data to the primary receiver, and in return leases its channel to the SUs for a fraction of time to transmit the SU data. The PU improves its performance with the assistance of SUs, while the SUs gain opportunities to access the PU's spectrum. Although the time-division spectrum sharing schemes create a “win-win” situation for both PUs and SUs, it introduces a high overhead to the PU's communications because the PU must completely give out a portion of its channel access time to the SUs in exchange for their cooperation in relaying the primary data [2]. Moreover, only one PU transmission link or network is considered in the previous studies.

On the other hand, Multiple-Input Multiple-Output (MIMO) [4,5] is an advanced physical layer technology that utilizes multiple antennas and spatial signal processing to offer several benefits. With MIMO, multiple data signal streams can be simultaneously transmitted and received on the same radio channel to increase wireless throughput, and one transmission link can suppress interference from neighboring links. By leveraging the MIMO beamforming capability in cooperative DSA, an SU may relay the PU data and transmit its own data at the same time. This will increase the flexibility in the design of the cooperation framework, and improve the performance of both PUs and SUs when compared to the time-division spectrum sharing schemes. Studies on how to take advantages of MIMO techniques and PU-SU cooperation to maximize system performance in the context of DSA remain limited. Most of them [6,7] focus on the physical layer and analyze the achievable transmission capacity from the information theory aspect without addressing the relay selection problem. To obtain the full benefits, the higher-layer PU-SU cooperation mechanisms should exploit the capabilities brought by cognitive radio and MIMO technologies in a systematic way. In the literature, a MIMO-based DSA scheme was proposed [8], in which an ad hoc SU network utilizes the MIMO antennas to cooperatively relay the traffic for a single PU link. In [13–15], cooperative spectrum leasing schemes are investigated, which incorporate MIMO and distributed interference alignment.

However, the above existing schemes mainly focus on how a

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particular primary link interacts with the SUs. They employ the Stackelberg game approach, where the PU is the leader, and the SUs are followers, to determine the optimal relay selection. In practice, multiple PU transmission links usually exist in a neighborhood, each on a different frequency channel, for example, in multi-channel OFDM cellular networks with multiple users and base stations [9]. Multiple SUs can dynamically access these PU channels, and assist the PU transmissions using MIMO cooperative relaying, while simultaneously transmitting their own data. When multiple PUs coexist with multiple SUs, the PUs will compete with each other in selecting a good SU as the partner for relaying their data, and the SUs also compete for spectrum resources. The impact of other PU links should be taken into consideration in assigning a SU relay for a PU link. This many-to-many relay selection problem with MIMO techniques has not been investigated before. The existing solutions for a single PU link, such as the Stackelberg games, are no longer applicable because they do not consider the competition of PUs in the SU relay selection. The new optimal relay selection scheme needs to be developed under the new scenario. Due to MIMO and multiple frequency channels, the PU and SU transmissions should be intelligently scheduled in temporal, frequency, and spatial domains to exploit channel and user diversities for optimal resource use. The following challenges should be addressed: (a) which SU relay is assigned toa certain PU transmission so that all the parties obtain benefits, and the overall system performance is optimized? (b) How should the PUs fairly share the spectrum with the SUs? (c) How should the SUs use MIMO resources for relaying the primary data and transmitting their own data?

In this paper, we propose a MIMO-based cooperative DSA framework that enables multiple PUs and multiple SUs for dynamic spectrum sharing. Particularly, we study the relay selection optimization problem among multiple PU links and multiple MIMO SU relays. The model is formulated as a bargaining game, and an algorithm is developed to derive the optimal PU-SU relay assignment as well as resource allocation. Evaluation results show that the proposed MIMO cooperative spectrum sharing scheme improves the utilities of both PUs and SUs.

2. System model

We consider the MIMO-based cooperative dynamic spectrum access system as sketched in Fig. 1. Multiple PU networks collocate with multiple MIMO cognitive SU networks. There are multiple concurrent PU transmissions, each operating on a licensed frequency channel from a primary transmitter (PT) to a primary receiver (PR). Multiple MIMO-empowered SUs are seeking to exploit possible transmission opportunities on these PU channels. We assume that the primary users are legacy users. They may not have MIMO capabilities. In our design, PUs are not required to change their hardware to support MIMO. Note that our relay selection and system optimization framework can be extended to the scenarios with more complex MIMO transceiver architectures [4,5].

The dynamic spectrum access and sharing occur among PU links and SUs that seek each other as partners. If a PU link and a SU form a partnership, the SU would cooperatively relay the primary traffic from the PT to the PR to improve the throughput of the PU link in a decode-and-forward relaying mode, while simultaneously accessing the PU spectrum to transmit and receive its own data by utilizing its MIMO beamforming capability. MIMO beamforming [4] is a spatial signal processing technique by which a transmitter can use multiple antennas to steer beams towards the desired receivers to increase the signal-to-noise ratio (SNR) while forming nulls at the undesired receivers to avoid interference, and a MIMO receiver is able to receive the desired signals together with suppressing interference from the undesired signals. For the sake of fairness and the limitation of SU's power, we assume in this paper that each PU link is limited to select at most one SU relay, and one SU can serve at most one PU link. There exist competitions among the PUs, as well as among the SUs during relay selection and partner matching.

This model fits many practical scenarios. The PU networks may be infrastructure-based (e.g. 3 G or 4 G cellular networks) or infrastructure-less (e.g. mobile ad hoc networks). For the infrastructure-based case, the PTs in Fig. 1 are the cellular base stations (BSs) and the PRs are the mobile devices, or vice versa. The BSs may belong to different network operators, such as AT & T and Verizon, operating on the different bands of the licensed spectrum. For the infrastructure-less case, PU nodes, for example wireless microphones and receivers operating on the TV band, may be either directly connected or connected indirectly through a multi-hop path. More generally, secondary networks may be mobile local area networks, cognitive hotspots, or femtocells, each led by a MIMO SU access point and seeking spectrum to improve its performance, or an ad hoc network.

Consider that the data transmissions are divided into time slots. The PT will decide whether to use the entire slot for direct transmission to PR, or to employ cooperative relaying. In the cooperative relaying case, each time slot is further divided into two equal subslots as shown in Fig. 2. In the first subslot, PT transmits the primary data to the selected MIMO SU relay, SUr, meanwhile, SUr receives the secondary data from another SU, denoted as SUt. Using appropriate postcoding on the received signals over multiple antennas [4], SUr separates and decodes PU and SU signals based on their different spatial signatures. In the second subslot, SUr employs the transmit zero-forcing-beamforming (ZFTF) technique [5] to forward the primary traffic to PR, and to send its own secondary data to another SU, denoted as SUd, at the same time. It performs the ZFBF precoding on the transmitted signals so as to null out the interference of its own data signal to the PU receiver. Thus, the legacy PU receiver, PR, only receives the relayed PU data signal without interference, and does not have to have any MIMO capability. SUd extracts the SU data and suppresses the PU signal through appropriate postcoding. Note that due to varying channel conditions and mobility, a SU that fails competition in a time slot may be selected as a relay, and obtain an opportunity to access the spectrum in a future slot. In addition, the MIMO relay SUr dynamically allocates its power for relaying PU data and transmitting SU data slot-by-slot to achieve system optimization as discussed later.

To analyze the data rates that the PU link and the SU relay can achieve through the above MIMO-based cooperative relaying, we first assume that the PU link has selected SUr as cooperative relay. The data rate analysis results will be used in the network-wide optimization algorithm for relay selection and cooperation of multiple PU links and SUs, as described in the next section. The channels between nodes are modeled as frequency-dependent complex Gaussian random variables, invariant within each slot, but generally varying over the slots, i.e., Rayleigh block-fading channels [2]. If PT transmits data to PR directly

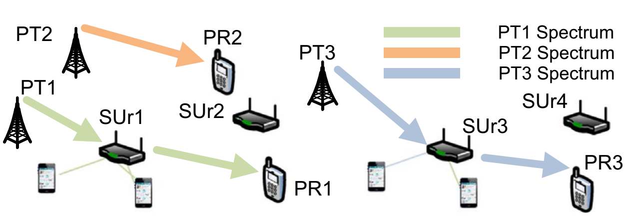

Fig. 1. Motivating scenario of MIMO cooperative DSA.

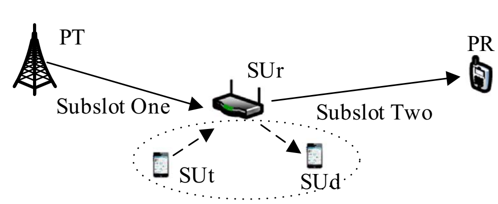

Fig. 2. MIMO cooperative relaying.