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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

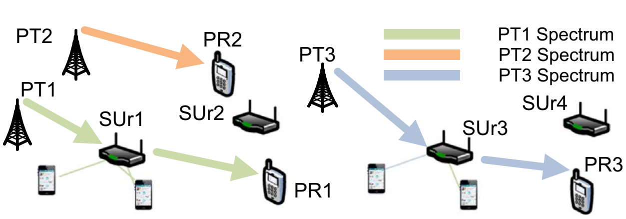

Fig. 1. Motivating scenario of MIMO cooperative DSA.

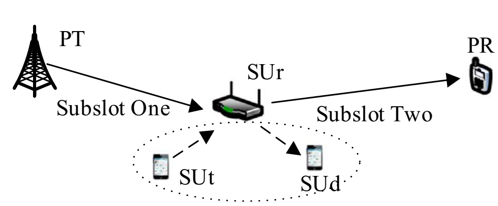

Fig. 2. MIMO cooperative relaying.

on channel c without relaying, the achievable rate is a function of the PT transmit power P_{pt} and the complex channel gain $h_{pt,pr}$ between PT and PR, which can be expressed as [3]

$$R_{pt,pr}^{dir} = log_2\left(1 + \frac{P_{pt} \mid h_{pt,pr} \mid^2}{N_0}\right), \tag{1}$$

where N_0 is the noise power. If PT decides to lease its channel to SUr for cooperative relaying, with the postcoding employed at SUr, then in the first subslot, the achievable rate on PT-SUr link is [4]

$$R_{pt,sr} = \frac{1}{2}log_2\left(1 + \frac{P_{pt} \mid \mathbf{v}_{\mathbf{pt,sr}}^{\mathbf{T}}\mathbf{h}_{\mathbf{pt,sr}} \mid^2}{N_0}\right), \tag{2}$$

where $\mathbf{v}_{\mathbf{pt,sr}}$ and $\mathbf{h}_{\mathbf{pt,sr}}$ are the decoding vector used by SUr to obtain PT's data and the channel coefficient vector from PT to SUr, respectively. The achievable rate SUr receives its own data from SUt in the first subslot is

$$R_{st,sr} = \frac{1}{2}log_2\left(1 + \frac{P_{st} \mid \mathbf{v}_{\mathbf{st,sr}}^{\mathbf{T}}\mathbf{H}_{\mathbf{st,sr}}\mathbf{u}_{\mathbf{st,sr}} \mid^2}{N_0}\right), \tag{3}$$

where $\mathbf{v}_{\mathbf{st,sr}}$, $\mathbf{H}_{\mathbf{st,sr}}$ and $\mathbf{u}_{\mathbf{st,sr}}$ are respectively the decoding vector used by SUr to obtain its own data, the channel coefficient matrix from SUt to SUr, and the encoding vector used by SUt to transmit the secondary data. In the second subslot, SUr uses the PU spectrum for forwarding the PU data and for sending its own data with transmit-side ZFBF. The achievable rates for the PU data and SU data transmissions are [5]

$$R_{sr,pr} = \frac{1}{2}log_2\left(1 + \frac{P_{sr,\ pr}|\mathbf{h}_{\mathbf{sr,pr}}\mathbf{u}_{\mathbf{sr,pr}}|^2}{N_0}\right), \tag{4}$$

$$R_{sr,sd} = \frac{1}{2}log_2\left(1 + \frac{P_{sr,sd}\left|\mathbf{v}_{\mathbf{sr,sd}}^{\mathbf{T}}\mathbf{H}_{\mathbf{sr,sd}}\mathbf{u}_{\mathbf{sr,sd}}\right|^2}{N_0}\right), \tag{5}$$

where $P_{sr,pr}$ and $P_{sr,sd}$ are the transmission powers that SUr allocates for the PU data relaying and the SU data transmission, respectively. $\mathbf{u}_{\mathbf{sr,pr}}$, $\mathbf{u}_{\mathbf{sr,sd}}$, and $\mathbf{v}_{\mathbf{sr,sd}}$ are the encoding and decoding vectors, respectively. $\mathbf{h}_{\mathbf{sr,pr}}$ and $\mathbf{H}_{\mathbf{sr,sd}}$ are the channel coefficient vector from SUr to PR and the channel coefficient matrix from SUr to SUd, respectively. Note that the channel coefficients are a function of the spectrum frequency.

From the above analysis, we can see that a set of strategies affect the achievable rates of PU and SU transmissions, including (i) PT should decide whether to use its frequency channel for direct transmission from PT to PR, or for SU relaying. (ii) In the latter case, the MIMO SU relay, SUr, needs to be assigned. (iii) In the second subslot, SUr needs to determine its MIMO relay strategy and power allocation for transmitting PU data and SU data. The MIMO SU relay should forward all the data received from its cooperating PT to the PR since the primary data has higher priority, thus satisfying the flow conservation constraint:

$$R_{pt,sr} = R_{sr,pr}. \tag{6}$$

In addition, the power allocation should be subject to the MIMO SU total power constraint:

$$P_{sr,\ pr} + P_{sr,\ sd} \le P_{sr}, \tag{7}$$

where P_{sr} is the allowed total transmission power of SUr. Note that the power allocation for PU and SU data transmissions at the MIMO SU relay can be obtained by substituting (2), (4) and (5) into (6) and (7) once the optimal MIMO SU relay is selected for a PU link. The relay selection optimization problem is discussed in the next section.

3. System Optimization

The optimal strategy of an entity depends on the behaviors of other entities as there are multiple PUs and SUs to compete in the system. For example, the PU links may have better chances to select good MIMO SU relays if there are more SUs participating in the competition for the spectrum. We model the system of multiple PUs and multiple SUs as a bargaining game, and study the relay selection strategy for overall system optimization.

Let $\mathcal{P}$ denote the set of PU links and $\mathcal{S}$ the set of MIMO SUs. We define the utility that each party can earn as its achievable rate, which is a function of relay selection, transmit power, and MIMO transmission states. If PU link i, $i\in\mathcal{P}$ uses SU j, $j\in\mathcal{S}$ as a relay, the utility of PU link i is defined as the achievable data rate with this partnership, $U_P^{(i,j)}=R_{pt,sr}^{(i,j)}$. The utility of SU relay j is the sum of the achievable rates that it receives and transmits its own data on the channel leased from PU link i, $U_s^{(i,j)}=R_{st,sr}^{(i,j)} + R_{sr,sd}^{(i,j)}$. The data rates are obtained from equations (2)–(5) in the last section. Note that our framework can also support other types of utility functions.

We formulate this relay selection problem as an N-player bargaining game and consider the long-term Nash Bargaining Solution (NBS) as our objective. Let $\mathcal{N} = \mathcal{P} \cup \mathcal{S}$ denote the set of players, including PUs and SUs. U_n^{dir},$n\in\mathcal{N}$ denotes the utility that the nth player expects if it does not cooperate with others. In order for player n to cooperate, its achievable utility $U_n$should be greater than U_n^{dir}, that is, $U_n > U_n^{dir}$. Otherwise, player n will not participate in the relay selection game. For a PU link, its utility by cooperating with a SU relay should be greater than that if it chooses to transmit directly from the PT to the PR without cooperation, i.e. $U_p > U_p^{dir}$and$U_p^{dir} =R_{pt,pr}^{dir}$. For a SU, the requirement is that its utility with cooperation should be greater than zero, i.e. $U_s > U_s^{dir}$andU_s^{dir}=0, because the SU cannot obtain spectrum to transmit without cooperation. The NBS is a unique Pareto optimal operation point that satisfies the axioms of fairness [10]. It can be achieved by solving the following,

$$\max_{U_n > U_n^{dir}} \prod_{n\in\mathcal{P}\cup\mathcal{S}} (U_n - U_n^{dir}) \tag{8}$$

For our problem, we wish to consider the long-term NBS, which depends on the average utility gain by cooperation. Let $\overline{U}_n$ and $\overline{U}_n^{dir}$ denote the average utility for player n with and without cooperative relaying, respectively. The problem is then to find the NBS, i.e. solving the optimization problem (8) with $\overline{U}_n$ and $\overline{U}_n^{dir}$. It is equivalent to solving,

$$F = \max_{\overline{U}_n > \overline{U}_n^{dir}} \sum_{n\in\mathcal{P}\cup\mathcal{S}} ln(\overline{U}_n - \overline{U}_n^{dir}) \tag{9}$$

The utility maximization problem has to be solved in every transmission slot because channel qualities change over time. Further, it has been shown that maximizing the aggregate marginal utility $\sum F'(\overline{U}_n)U_n$ at each slot achieves the long-term utility maximization [11]. We thus maximize $\sum F'(\overline{U}_n)U_n$, that is, $max \sum_{n\in\mathcal{P}\cup\mathcal{S}} \frac{U_n}{\overline{U}_n(t) - \overline{U}_n^{dir}(t)}$, where $\overline{U}_n(t)$ and $\overline{U}_n^{dir}(t)$ are the average utility for player n at slot t with and without cooperative relaying, respectively.

Define $d_k \in \{0,1\}$, $k\in\mathcal{P} \cup \mathcal{S}$ as a variable to indicate whether entity k chooses to participate in cooperative relaying (d_k=0) or not (d_k=1), and $x_{ij} \in \{0,1\}$, $i\in\mathcal{P}$,$j\in \mathcal{S}$ as a variable to indicate whether j is a relay of i (x_{ij}=1) or not (x_{ij}=0). We set $\alpha_n(t) = \frac{1}{\overline{U}_n(t) - \overline{U}_n^{dir}(t)}$. The problem is then to decide whether a PU link should use the cooperative relaying or the direct transmission, as well as the optimal relay selection, that is, d_k and x_{ij} in each time slot t, so that the utility is maximized,

$$\max\left\{\sum_{i\in\mathcal{P}}\sum_{j\in\mathcal{S}} x_{ij}(\alpha_i(t)U_p^{(i,j)} + \alpha_j(t)U_s^{(i,j)}) + \sum_{k\in\mathcal{P}\cup\mathcal{S}} d_k\alpha_k(t)U_k^{dir}\right\}, \tag{10}$$

subject to: MIMO SU relay flow conservation constraint (6) and relay power constraint (7), as well as the following constraints,

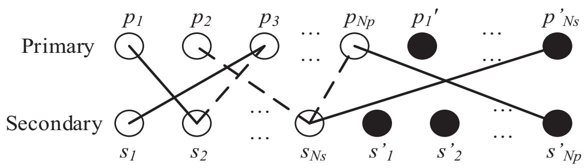

Fig. 3. Bipartite graph construction.

$$\sum_{i\in\mathcal{P}} x_{ij} + d_j=1, \quad \forall j\in\mathcal{S} \tag{11}$$

$$\sum_{j\in\mathcal{S}} x_{ij} + d_i=1, \quad \forall i\in\mathcal{P} \tag{12}$$

The above optimal relay selection problem is an assignment problem, i.e., assigning a MIMO SU j to a PU link i as relay. The objective is to find the assignment of the SU relays to the PU links that yields the maximum total weight, (10). It can be solved by weighted bipartite matching [12]. A bipartite graph can be constructed as shown in Fig. 3. Each primary link i; $i = 1, \ldots, N_P$ is represented by a vertex p_i in the upper part of the graph, and each potential MIMO SU relay j; $j = 1, \ldots, N_S$ is represented as a vertex s_j in the lower part of the figure. An edge connecting vertices p_i and s_j indicates that SUr j is assigned to PU link i as relay. The weight on the edge is set to be $\alpha_i(t)U_p^{(i,j)} + \alpha_j(t)U_s^{(i,j)}$ according to (10). Moreover, to characterize the entities that do not participate in the cooperative relaying, we add N_S virtual vertices $p_1',\ldots,p_{N_S}'$ and N_P virtual vertices $s_1',\ldots,s_{N_p}'$ to the upper and lower parts of the graph, respectively. We assign the weight $\alpha_i(t)U_i^{dir}$ to the edge connecting p_i and s'_i, $i = 1, \ldots, N_P$, which captures the utility given by the direct transmission of primary link i. Similarly, the edge connecting vertices s_j and p_j', $j = 1, \ldots, N_S$ is assigned the weight $\alpha_j(t)U_j^{dir}$, indicating SUr j does not cooperate with any primary link. Observe that the optimal relay assignment, (10), is equivalent to finding a PU-SU matching that maximizes the sum weight in this bipartite graph, which can be optimally solved by using the Hungarian method in polynomial time [12]. The complexity of the algorithm is $O((N_P + N_S)^4)$.

4. Performance evaluation

In this section, we evaluate the performance of the proposed many-to-many MIMO cooperative DSA optimization framework. We consider there exist N_P PU transmission links and N_S potential MIMO SU relays. All the PTs are placed at a location A, which serves as the transmitter location of all the primary links, just like a cellular tower. The PRs are randomly distributed in a circle with a radius of 100 m centered at A. Moreover, the MIMO SU relays are randomly distributed within the circle. Each SUr receives the secondary data from a SUt and sends the secondary data to a SUd. The SUt and SUd are randomly placed in a circle centered at the SUr with a radius of 30 m. In addition, we assume that each PU link operates on a frequency channel with a bandwidth of 1 MHz in 700 MHz band. The thermal noise level is set to be −130 dBm. The transmission power of PT, P_{pt}, is set to be a value such that the average channel SNR of the primary links is 0 dB. The total transmission powers of SUr and SUt are set to be $1.0\times P_{pt}$ and $0.5 \times P_{pt}$, respectively. We further assume that all the PTs and PRs are equipped with a single antenna, while all the SUs are equipped with two antennas with MIMO transceivers. Moreover, the channel is modeled as a large-scale path loss component with a path loss exponent of $\eta = 4$, and a small-scale Rayleigh fading component with $\sigma = 1$.

Figs. 4 and 5 demonstrate the system performance with SU relay density. The number of PU links is 20. The presented results are the averages over 20 random topologies. The “No Cooperation” in the figures means that there is no cooperative SU relaying, and a PT directly transmits its data to a PR. The “Time-Domain” cooperative DSA scheme is similar to the scheme proposed in [2,3], in which the cooperation between a PU transmission and a SU relay adopts a time-division multiplexing protocol to share the channel. We can see from the figures that by exploiting MIMO-based cooperative SU relaying, the proposed DSA scheme achieves the highest PU and SU utilities. The results validate that our MIMO cooperative DSA framework can achieve big win-win gains for both PUs and SUs. Additionally, Fig. 4 shows the PU utility improves as N_S increases because more SUs result in more opportunities for the PU links to find suitable cooperative relays. Fig. 5 shows that the SU utility decreases as N_S increases because more SUs compete to access the limited spectrum resource.

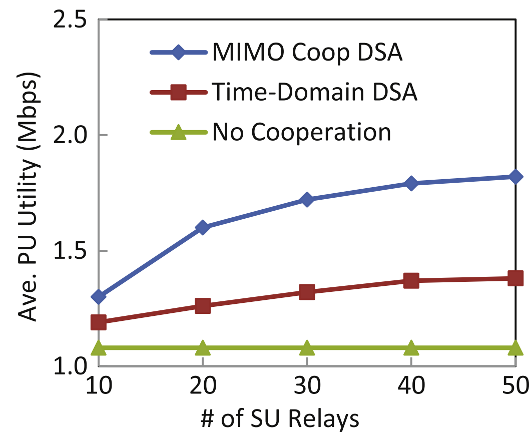

Fig. 4. Utility of PU versus SU relay density.

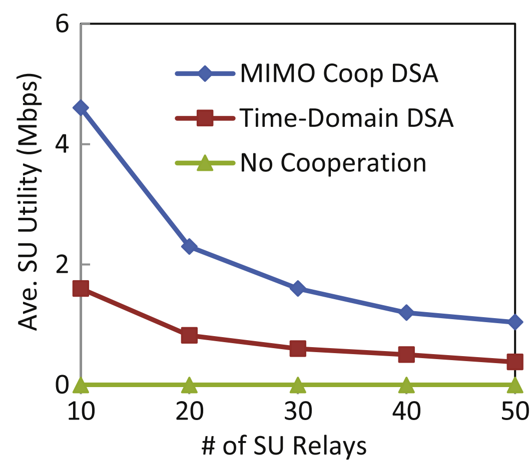

Fig. 5. Utility of SU versus SU relay density.

Figs. 6 and 7 illustrate the utilities of PU and SU versus the number of PU links. In Fig. 6, the PU utility decreases for the MIMO

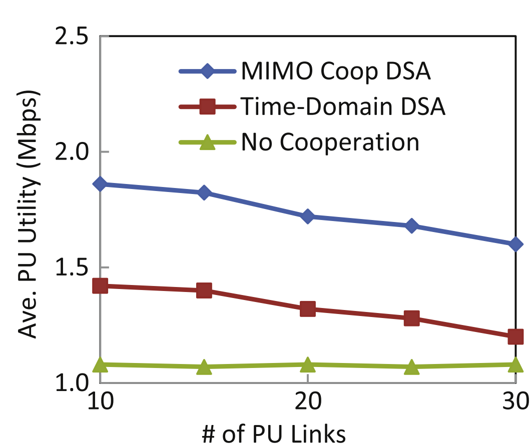

Fig. 6. Utility of PU versus the number of PU links.

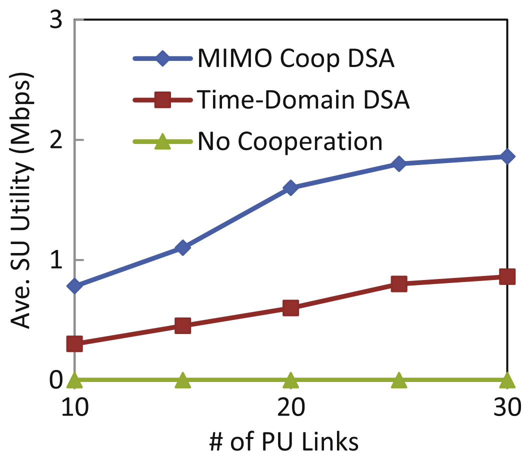

Fig. 7. Utility of SU versus the number of PU links.

cooperative DSA and time-domain DSA schemes as N_P increases because more PU links compete for good SU relays, and some of PUs may not be able to find suitable relays. In Fig. 7, the SU utility improves with N_P increased because a SU is more likely to be selected as a relay for a PU link and access the PU's spectrum for its own data transmission. As shown in Figs. 6 and 7, the MIMO cooperative DSA scheme significantly outperforms the direct transmission and time-domain cooperative DSA schemes.

5. Conclusions

In this paper, we present a novel framework that enables multiple PUs and multiple MIMO SUs to cooperate for dynamic spectrum sharing. By leveraging the MIMO capability, SUs help relay the primary traffic while concurrently accessing the PUs’ spectrum to transmit their own data. The optimization algorithm for the PU-SU relay assignment and cooperation is proposed and further analyzed. Evaluation results show that both PUs and SUs can benefit from the proposed framework.

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