Exploiting MIMO Antennas in Cooperative Cognitive Radio Networks

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Abstract—**Recently, a new paradigm for cognitive radio networks has been advocated, where primary users (PUs) recruit some secondary users (SUs) to cooperatively relay the primary traffic. However, all existing work on such cooperative cognitive radio networks (CCRNs) operate in the temporal domain. The PU needs to give out a dedicated portion of channel access time to the SUs for transmitting the secondary data in exchange for the SUs' cooperation, which limits the performance of both PUs and SUs. On the other hand, Multiple Input Multiple Output (MIMO) enables transmission of multiple independent data streams and suppression of interference via beam-forming in the spatial domain over MIMO antenna elements to provide significant performance gains. Researches have not yet explored how to take advantage of the MIMO technique in CCRNs. In this paper, we propose a novel MIMO-CCRN framework, which enables the SUs to utilize the capability provided by the MIMO to cooperatively relay the traffic for the PUs while concurrently accessing the same channel to transmit their own traffic. We design the MIMO-CCRN architecture by considering both the temporal and spatial domains to improve spectrum efficiency. Further we provide theoretical analysis for the primary and secondary transmission rate under MIMO cooperation and then formulate an optimization model based on a Stackelberg game to maximize the utilities of PUs and SUs. Evaluation results show that both primary and secondary users achieve higher utility by leveraging MIMO spatial cooperation in MIMO-CCRN than with conventional schemes.**

I. INTRODUCTION

Cognitive radio, with the capability to flexibly adapt its transmission or reception parameters, has been proposed as the means for unlicensed secondary users (SUs) to dynamically access the licensed spectrum held by primary users (PUs) in order to increase the efficiency of spectrum utilization. Recently, a new paradigm termed Cooperative Cognitive Radio Networks (CCRNs) has been advocated [1]. In CCRN, PUs may select some SUs to relay the primary traffic cooperatively, and in return grant portion of the channel access time to the SUs. By exploiting cooperative diversity, the transmission rates of PUs can be significantly improved. SUs, being the cooperative relays, as a consequence obtain opportunities to access the channel for their own data transmissions. This results in a "win-win" situation. All existing CCRN-based schemes [1], [2], [3], [4] operate in the temporal domain, assuming each PU or SU is equipped with a single antenna. In particular, a frame duration is time-divided into three phases. The first phase is used for the primary transmitter to broadcast the data to the relaying SUs. In the second phase, those SUs form a distributed antenna array to cooperatively relay the primary data to the primary receiver, improving the throughput of the primary link. In return, the third phase is leased to the SUs for their own traffic.

Although the conventional CCRN framework benefits both the PUs and SUs, there still exist some inefficiencies. First, the PU must completely give out its spectrum access to the SUs for their transmissions in the third phase, as a reward for the SUs to help relay the primary data. To incentivize the SUs to participate in the cooperation, the duration of the third phase should be set reasonably large so that the throughput that the SUs can earn could compensate the power they have consumed in the previous relay transmission. This introduces a high overhead to the PUs' communication. Second, the SUs' transmissions are confined to the third phase. Considering there will be multiple secondary links competing for spectrum access, this phase will become crowded. As a result, the throughput each secondary link can achieve is limited.

To address the above problems, we propose a novel design called the **MIMO-CCRN** framework for cooperation among SUs and PUs by exploiting MIMO antennas on SUs' transceivers. MIMO is a physical layer technology that can provide many types of benefits through multiple antennas and advanced signal processing. Multiple independent data streams can be transmitted or received over the MIMO antenna elements. Furthermore MIMO can also realize interference suppression. Through beam-forming, a MIMO receiver can suppress interference from neighboring transmitters and a MIMO transmitter can null out its interference to other receivers. Given its potential, MIMO has been adopted in next-generation WiFi, WiMax, and cellular network standards. However researchers have not explored how to take advantage of the MIMO techniques in the context of CCRN.

The basic idea of MIMO-CCRN can be explained using an example, as shown in Fig. 1. We consider a pair of PUs, each with a single antenna, co-located with several SUs seeking transmission opportunities. The SU's are equipped with multiple antennas. The primary link may share the resource in time/frequency with other PUs in the primary system, e.g., a TDMA/OFDMA based infrastructure-based network. It can customize its share of resources to improve its performance by

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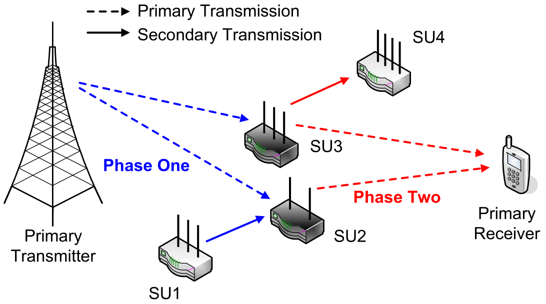

Fig. 1. The motivating scenario for MIMO-CCRN.

recruiting SUs as the relays. Assume SU_2 and SU_3 are selected as the relays. A time period is then divided into two phases. In Phase One, the primary transmitter broadcasts data to SU_2 and SU_3. Meanwhile, SU_2 can simultaneously receive its own traffic from another SU, SU_1, as long as the total number of primary and secondary streams is no greater than its antenna Degree-of-Freedom (DoF). Similarly in Phase Two, SU_2 and SU_3 cooperatively forward the primary data to the primary receiver. At the same time, SU_3 is able to transmit its own data to SU_4 using beam-forming if it ensures the interference from the secondary stream is cancelled at the primary receiver. As we can see, in the MIMO-CCNR framework, the SUs utilize the capability provided by the MIMO to cooperatively relay the traffic for the PUs while concurrently obtaining opportunities to access the spectrum for their own traffic. The PU does not need to allocate a dedicated fraction of channel access time to SUs. Furthermore, the PU can still use legacy devices and is not required to change its hardware to support MIMO capability. MIMO-CCRN can greatly improve the performance of both PUs and SUs. Of course, the trade-off is that the SUs must be equipped with sophisticated MIMO antennas, which are expected to be widely adopted in future radio devices.

We focus on the cross-layer design and performance analysis of the proposed MIMO-CCRN framework. We are interested in answering the following questions: what are the benefits of exploiting MIMO in the context of CCRN; how the primary link selects the MIMO SUs as cooperative relays; and what strategies the SUs use to relay the primary data and transmit their own traffic using MIMO antennas. Given that both PUs and SUs target at maximizing their own utilities, we model the MIMO-CCRN framework as a Stackelberg game and characterize the benefits of cooperation using MIMO. Specifically, the contributions of this paper are three-fold:

1) We propose a novel MIMO-CCRN system architecture. By leveraging MIMO capability, the SUs access the spectrum to relay the primary data and simultaneously transmit their own data as a reward for being the relays. By carefully considering the DoFs of the nodes, we schedule the transmissions in both the spatial and temporal domains to improve the spectral efficiency. A theoretical formulation for the primary/secondary link capacities under MIMO cooperation is provided.

2) To maximize the performance, we formulate MIMO-CCRN as a Stackelberg game. Specifically, the PUs act as the leader who determine the strategy on the relay selection and the durations of different phases to optimize its utility. SUs act as the followers which conduct a power control game, with the target of maximizing their individual utilities. A unique Nash Equilibrium is achieved which provides the optimal strategy.

3) We evaluate the performance of MIMO-CCRN. Simulation results show that under our framework, by leveraging MIMO techniques, both PUs and SUs achieve higher utilities than the conventional CCRN schemes.

The remainder of the paper is organized as follows. Related work is described in Section II. Section III presents an overview of MIMO and its potential benefits. In Section IV, we describe the MIMO-CCRN system model and formulate the primary utility maximization problem. The problem is analyzed using game theory in Section V and an optimal strategy is determined. Simulation results are presented and discussed in Section VI. Conclusions are presented in Section VII.

II. RELATED WORK

There have been extensive studies of cognitive radio in recent years. Leveraging cooperative diversity to enhance the performance of cognitive radio networks has attracted much attention. One category of work focuses on the cooperation between SUs. In [5], by exploiting the spectrum-rich but low traffic demand SUs to relay the data for other SUs, the overall performance of the secondary network can be improved. A relay-assisted routing protocol exploiting such spectrum heterogeneity was then proposed in [6]. Another category termed CCRN, concentrates on the cooperative communication between PUs and SUs. O. Simeone et al. [1] proposed the paradigm in which the primary link may decide to lease the spectrum for a fraction of time to the SUs in exchange for their cooperation in relaying the primary data. This concept has been further extended to combine the pricing of the spectrum in [2], and to the multi-channel scenario in [3]. Recently, it was also studied in a dual infrastructure-based cognitive radio network with multiple primary links [4]. However, the previous work does not leverage the spatial domain in the cooperative transmission when the nodes are equipped with multiple antennas. We consider this setting and seek to provide a practical paradigm taking advantage of the MIMO technique.

MIMO has been widely accepted as a key technology to increase wireless capacity. Extensive research work on MIMO have been done at the physical layer for point-to-point and cellular communications [7]. Many researchers have exploited the benefits of MIMO from a cross-layer prospective. In wireless mesh networks, the throughput optimization problem based on MIMO was studied in [8], [9], [10]. MIMO-aware MAC and routing mechanisms are presented in [11], [12]. In wireless sensor networks, MIMO has also been applied to improve energy efficiency [13], and to enhance the performance of data gathering [14]. However, the studies on MIMO in cognitive radio networks remain limited and mainly focus on the physical layer, as in [15], [16]. Our work bridges this gap and focuses on cross-layer design in the context of CCRN.

III. PRELIMINARIES: MIMO CHARACTERISTICS

In this section, we briefly explain the basics of MIMO and its benefits. Since MIMO is a broad category containing various techniques, we will mainly focus on introducing Zero-Forcing Beam-Forming (ZFBF), which is intensively used in our MIMO-CCRN framework design.

A. Zero-Forcing Beam-forming

ZFBF is one of the most powerful interference mitigation techniques in MIMO systems [17], [18]. It uses multiple antennas to steer beams towards the intended receivers to increase the Signal-to-Noise Ratio (SNR), while forming nulls at unintended receivers to avoid interference. Such beamforming can be performed on both transmitter and receiver sides through appropriate pre- and post-coding on the signals. Since ZFBF performs linear correlation/decorrelation with low complexity, it provides a tractable solution suitable for use in many MIMO-based cross-layer designs [8], [9], [14].

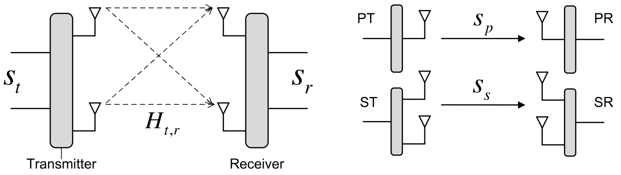

Fig. 2. Transmission of two streams: a 2 × 2 MIMO channel (left) and a multi-user MIMO scenario (right).

For ease of explanation, let us start with the standard 2×2 MIMO channel to understand the rationale of ZFBF, as shown in the left part of Fig. 2. Two streams, s_1 and s_2, can be transmitted simultaneously through this MIMO link without interference. Before transmission, precoding can be performed on the two streams by multiplying the stream s_i with an *encoding vector* $\mathbf{u_i} = [u_{i1} \; u_{i2}]^T$. Therefore, the resulting transmitted signal will be $\mathbf{s_t} = \mathbf{u_1}s_1 + \mathbf{u_2}s_2$. Each antenna transmits a weighted combination of the original stream s_1 and s_2.

Let $\mathbf{H_{t,r}}$ denote the 2×2 channel matrix between the transmitter and the receiver. Each entry h_{ij} of $\mathbf{H_{t,r}}$ is a complex channel coefficient along the path from the j^{th} antenna on the transmitter to the i^{th} antenna on the receiver. Therefore, we can represent the received signals on the receiver side as:

$$\mathbf{s_r} = \mathbf{H_{t,r}s_t} + \mathbf{n} = \mathbf{H_{t,r}u_1}s_1 + \mathbf{H_{t,r}u_2}s_2 + \mathbf{n} \qquad (1)$$

where $\mathbf{n}$ is the i.i.d. $\mathcal{CN}(0, \sigma^2\mathbf{I_2})$ channel noise. Since the receiver has two antennas, representing the signals as 2-dimensional vectors is convenient [19]. We can see that the receiver actually receives the sum of two vectors which are along the directions of $\mathbf{H_{t,r}u_1}$ and $\mathbf{H_{t,r}u_2}$. The encoding vectors $\mathbf{u_1}$ and $\mathbf{u_2}$ control the direction of the vectors.

Eqn. 1 shows that the two streams interfere with each other on the receiver side. An idea to remove such inter-stream interference is to project the received signal $\mathbf{s_r}$ onto the subspace orthogonal to the one spanned by the other signal vector. Specifically, we can apply two *decoding vectors* $\mathbf{v_1}$ and $\mathbf{v_2}$ on $\mathbf{s_r}$ to decode s_1 and s_2 respectively as

$$\tilde{s}_i = \mathbf{v_i}^\dagger\mathbf{H_{t,r}u_1}s_1 + \mathbf{v_i}^\dagger\mathbf{H_{t,r}u_2}s_2 + \mathbf{v_i}^\dagger\mathbf{n} \quad i = 1, 2 \qquad (2)$$

If we judiciously configure the encoding and decoding vectors in a way that $\mathbf{v_1}^\dagger\mathbf{H_{t,r}u_2} = \mathbf{0}$ and $\mathbf{v_2}^\dagger\mathbf{H_{t,r}u_1} = \mathbf{0}$, the two streams s_1 and s_2 can be decoded without interference. ZFBF can thus realize *spatial multiplexing* of the streams. In the situations where the co-channel interference is much stronger than the noise, the channel capacity can be significantly improved.

B. ZFBF in multi-user MIMO scenarios

The above example shows how to manipulate the encoding and decoding vectors to nullify the interference in a single user-pair case. More often than not, ZFBF is adopted as an interference mitigation technique in multi-user MIMO scenarios [17], [18], like cellular uplink/downlink. We will briefly illustrate it in the context of cognitive radio networks as follows, which is also the model presented in [16]

The right part of Fig. 2 shows an example in which ZFBF improves the spatial reuse of the channel with multiple users. Consider that a pair of PUs, each equipped with one antenna, forms a primary link. A pair of SUs forms a secondary link with each SU equipped with two antennas. The primary link and secondary link are within each other's interference range. The channel coefficient matrices between different transmitter/receiver combinations are denoted as $h_{PT,PR}$, $\mathbf{h}_{PT,SR}$, $\mathbf{h}_{ST,PR}$ and $\mathbf{H}_{ST,SR}$. Note that depending on the number of transmitting and receiving antennas, their dimensions are 1×1, 2×1, 1×2 and 2×2 respectively.

Two independent streams, one primary stream s_p and one secondary stream s_s, can be transmitted simultaneously. Suppose the encoding and decoding vectors applied on the secondary link are $\mathbf{u}_s$ and $\mathbf{v}_s$, the final signals on both primary and secondary receivers are

$$\begin{aligned} \tilde{s}_p &= h_{PT,PR}s_p + \mathbf{h}_{ST,PR}\mathbf{u_s}s_s + n_p \\ \tilde{s}_s &= \mathbf{v}_s^\dagger\mathbf{h}_{PT,SR}s_p + \mathbf{v}_s^\dagger\mathbf{H}_{ST,SR}\mathbf{u}_s s_s + \mathbf{v}_s^\dagger\mathbf{n_s} \end{aligned} \qquad (3)$$

If we intentionally configure $\mathbf{u}_s$ and $\mathbf{v}_s$ so that $\mathbf{h}_{ST,PR}\mathbf{u}_s = 0$ and $\mathbf{v}_s^\dagger\mathbf{h}_{PT,SR} = \mathbf{0}$, both primary and secondary signals can be decoded at their corresponding receivers. In this example, the co-channel interference is suppressed due to ZFBF. The spatial reuse factor is improved by letting two interfering links transmit simultaneously, where the PUs' transmission is not affected as the SUs access the channel. The general case of the capacity of multi-user MIMO based on ZFBF is studied in [18]. Note the encoding/decoding vectors commonly have unit length.

C. Remarks on employing ZFBF

Although ZFBF can provide appealing benefits, several issues need to be carefully considered when employing it, which are discussed below:

1) To properly configure the encoding and decoding vectors, both transmitter and receiver should be aware of the instantaneous channel coefficient matrix. This is a common assumption in [18], [1], [3]. However even without such

assumption, there exist practical estimation techniques already being applied in implementations which give fairly good results [20].

2) The ability of ZFBF to enable *spatial multiplexing* and *suppress interference*, is not unlimited. Fundamentally, the number of concurrent streams that can be scheduled is constrained by the DoF of the transmitting node. Also, the number of streams a receiver can simultaneously receive is also limited by its DoF [10]. We will carefully consider the nodes' DoFs in scheduling the transmissions in MIMO-CCRN.

IV. SYSTEM MODEL

In this section, we describe the system model of the MIMO-CCRN framework. We resolve the achievable rates for both primary and secondary links and provide a theoretical formulation for the *primary utility maximization problem*. Due to the practical constraint on the distances between antennas to ensure independent fading, we will mainly consider the case that the SUs are equipped with two antennas. The general case of SUs equipped with multiple antennas is also discussed.

A. System Model Description

We consider a secondary network consisting of $K = |\mathcal{S}|$ transmitter-receiver pairs, each of which is denoted by (ST$_i$, SR$_i$), $i \in \mathcal{S}$. SUs are equipped with two MIMO antennas. Each PU is assumed to be a legacy device with a single antenna. They are co-located and all the entities interfere with each other. The primary transmission is divided into frames and we use T to represent the frame duration (FD). The primary link can select a subset of secondary pairs to participate in the cooperative transmission, denoted as $\mathcal{R}$. Either ST or SR in each pair can be the relay. Note that it gives more flexibility to PUs' relay selection compared to [1], [2], in which only STs can be chosen as the relay. Fig. 3 demonstrates the frame structure we use in MIMO-CCRN. If the cooperative communication is enabled, a FD is time-divided into two phases. In the first phase with duration αT, the Primary Transmitter (PT) broadcasts the primary data to the secondary relays in $\mathcal{R}$. Then in the second phase with duration $(1-\alpha)T$, those secondary relays cooperatively transmit the data to the Primary Receiver (PR). We define $\alpha = 1$ as a special case when PT uses the entire FD for a direct transmission to PR without cooperation. We can see that compared to the existing CCRN schemes, MIMO-CCRN totally avoids a time fraction dedicated for the SUs' transmissions. In return for the SUs' cooperation, the channel will be granted to the relays for their own traffic. As a result of the use of MIMO, their transmissions can be intelligently scheduled into the two phases. The detailed procedure is illustrated next.

1) Phase One: Fig. 3 shows the system architecture of MIMO-CCRN. In this example, there are $|\mathcal{S}| = 4$ pairs of SUs. We suppose the primary link selects SR$_1$, SR$_2$, ST$_3$ and ST$_4$ as the cooperative relays, which are marked in black in the figure. Throughout Phase One, PT continuously broadcasts its data to the chosen relays. For the secondary network, the pairs with SR selected as the relay are allowed to access the channel in this phase in a TDMA fashion. In our example, they are the pairs (ST$_1$, SR$_1$) and (ST$_2$, SR$_2$). We use $\mathcal{S}_1$ to denote the set of such pairs. Thus Phase One is further divided into $|\mathcal{S}_1|$ subslots ($|\mathcal{S}_1| = 2$ in our example), one for each pair. In a symmetric way, the pairs with ST selected as the relay, denoted by $\mathcal{S}_2$, are granted access the channel in Phase Two. It is obvious that $\mathcal{S}_1$ and $\mathcal{S}_2$ are disjoint sets and $\mathcal{S}_1 \cup \mathcal{S}_2 = \mathcal{R} \subseteq \mathcal{S}$.

We use $\mathbf{h}_{0r}$ to represent the channel coefficient vector from PT to the relay node r, $\forall r \in \mathcal{R}$. Note this node stands for SR$_r$ if $r \in \mathcal{S}_1$ and ST$_r$ if $r \in \mathcal{S}_2$. Also $\mathbf{H}_{ir}$ is used to represent the channel coefficient matrix from ST$_i$ to the relay node r, $\forall i \in \mathcal{S}_1, r \in \mathcal{R}$. Suppose a subslot of length $T_k^{(1)}$ is allocated to the pair (ST$_k$, SR$_k$), $k \in \mathcal{S}_1$ in Phase One, by virtue of multiple antennas, SR$_k$ can receive both streams from PT and ST$_k$ simultaneously in this subslot. We further denote the primary stream as s_p and the stream transmitted by ST$_k$ in this subslot as s_k. If ST$_k$ applies an encoding vector $\mathbf{u}_k^{(s)}$ on s_k, then the received signal on each relay r in this subslot is the combination of PT's stream and ST$_k$'s stream,

$$s_{r,k}^{(rec)} = \mathbf{h}_{0r} s_p + \mathbf{H}_{kr} \mathbf{u}_k^{(s)} s_k + \mathbf{n}, \qquad \forall\ r \in \mathcal{R}, k \in \mathcal{S}_1, \quad (4)$$

which can be viewed as the combination of two vectors in a two-dimensional space. Then each relay r can apply a decoding vector $\mathbf{v}_{r,k}^{(p)}$ to decode the primary stream, by letting $\mathbf{v}_{r,k}^{(p)\dagger} \mathbf{H}_{kr} \mathbf{u}_k^{(s)} = 0$. The resulting primary signal on r is then

$$\tilde{s}_{r,k}^{(p)} = \mathbf{v}_{r,k}^{(p)\dagger} \mathbf{h}_{0r} s_p + \mathbf{v}_{r,k}^{(p)\dagger} \mathbf{n}, \qquad \forall\ r \in \mathcal{R}, k \in \mathcal{S}_1. \quad (5)$$

Being one of the relays, SR$_k$ uses another decoding vector $\mathbf{v}_k^{(s)}$ to decode the secondary stream for itself. By letting $\mathbf{v}_k^{(s)\dagger} \mathbf{h}_{0k} = 0$, its own stream sent by ST$_k$ can be decoded as

$$\tilde{s}_k = \mathbf{v}_k^{(s)\dagger} \mathbf{H}_{kk} \mathbf{u}_k^{(s)} s_k + \mathbf{v}_k^{(s)\dagger} \mathbf{n}, \qquad k \in \mathcal{S}_1. \quad (6)$$

Therefore we can clearly see that in Phase One, the secondary relays continuously receive the primary data from the PT, meanwhile those pairs in set $\mathcal{S}_1$ perform their own transmissions in their respective subslots.

2) Phase Two: In Phase Two, a similar idea can be applied as in Phase One. The selected relays cooperatively forward the primary data to the PR, meanwhile, the pairs in the set $\mathcal{S}_2$ will access the channel in a TDMA fashion. As in Fig. 3, (ST$_3$, SR$_3$) and (ST$_4$, SR$_4$) share the channel by dividing it into two subslots, one for each pair.

We use $\mathbf{H}_{ri}$ to denote the channel coefficient matrix from relay r to SR$_i$, $\forall r \in \mathcal{R}, i \in \mathcal{S}_2$, and $\mathbf{h}_{r0}$ is used to represent the channel coefficient vector from relay r to PR. Also the node r stands for SR$_r$ if $r \in \mathcal{S}_1$ and ST$_r$ if $r \in \mathcal{S}_2$. Without ambiguity, we still use s_p and s_k to denote the primary stream and the secondary stream ST$_k$ sends. Suppose a subslot of length $T_k^{(2)}$ is allocated to the pair (ST$_k$, SR$_k$), $k \in \mathcal{S}_2$. Since ST$_k$ has multiple antennas, it can transmit both primary and secondary streams to the PT and SR$_k$ respectively without interference. Specifically, each relay r (including ST$_k$) transmits s_p encoded by $\mathbf{u}_{r,k}^{(p)}$. Meanwhile, ST$_k$ also transmits its own signal s_k

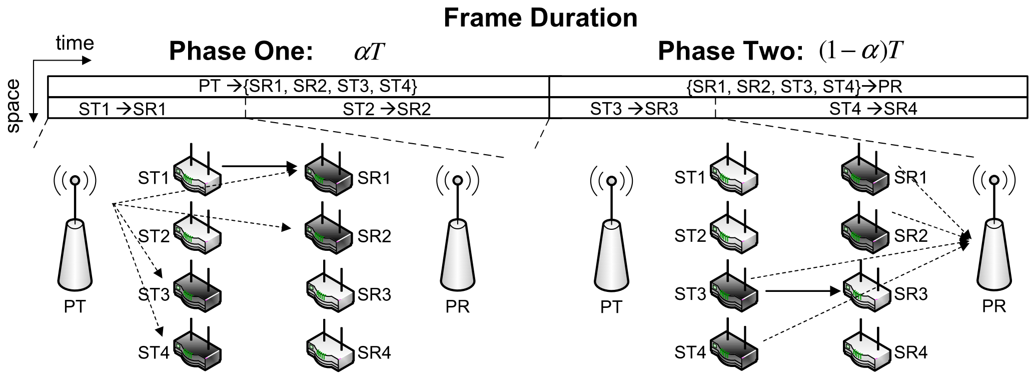

Fig. 3. System architecture and frame structure of MIMO-CCRN.

encoded with vector $\mathbf{u}_k^{(s)}$, which is combined with the primary signal it sends. If $\mathbf{u}_k^{(s)}$ is chosen so that $\mathbf{h}_{k0}\mathbf{u}_k^{(s)} = 0$, the secondary stream from ST_k is totally nulled at the PR. The signal received by PR is then

$$\tilde{s}_p = \sum_{r\in\mathcal{R}} \sqrt{P_r}\mathbf{h}_{r0}\mathbf{u}_{r,k}^{(p)} s_p + \mathbf{n}. \tag{7}$$

Moreover, the received signal for SR_k in this subslot is

$$s_k^{(rec)} = \sum_{r\in\mathcal{R}} \sqrt{P_r}\mathbf{H}_{rk}\mathbf{u}_{r,k}^{(p)} s_p + \mathbf{H}_{kk}\mathbf{u}_k^{(s)} s_k + \mathbf{n}, \tag{8}$$

$\forall\, r \in \mathcal{R}, k \in \mathcal{S}_2$. We use $P_r, r \in \mathcal{R}$ to denote the transmission powers used for relaying by relay r. The exact values of P_r's are determined by the secondary power control game described in Section V. The first part in Eqn. (8) is the primary signal summed over all the relays. The second part is the secondary signal transmitted by ST_k. The received signal $s_k^{(rec)}$ can be also represented as two vectors in a two-dimensional space. The secondary signal s_k can thus be easily decoded by choosing a decoding vectors $\mathbf{v}_k^{(s)}$ such that the primary signal can be canceled. The resulting secondary stream is

$$\tilde{s}_k = \mathbf{v}_k^{(s)\dagger}\mathbf{H}_{kk}\mathbf{u}_k^{(s)} s_k + \mathbf{v}_k^{(s)\dagger}\mathbf{n}, \qquad k \in \mathcal{S}_2. \tag{9}$$

In summary, in Phase Two the relays continuously forward the primary data to the PR, meanwhile those pairs in $\mathcal{S}_2$ perform their own transmissions in their respective subslots. Moreover, we will study how to resolve the length of each subslot in Phase One and Two, $T_k^{(1)}$ and $T_k^{(2)}$, in Section V.

B. Link Data Rate Analysis

Based on the system model described above, the data rates for both primary and secondary links can be resolved.

1) Primary Link: For the cooperative communication, we assume the use of a collaborative scheme based on decode-and-forward (DF) due to its simplicity in presentation, and at the receiving end, the PR exploits maximum ratio combining (MRC) before decoding the signal. Our scheme can be extended to use more sophisticated coding/decoding techniques to obtain a greater achievable primary rate.

In Phase One, since there are multiple relays in the downlink, the rate is easily shown to be dominated by the worst channel in the subset $r \in \mathcal{R}$. Suppose the transmission power of PT is P_P, according to Eqn. (5), in the subslot when ST_k is transmitting, the downlink rate is

$$R_k^{(PS)} = \log_2\left(1 + \frac{\min_{r\in\mathcal{R}} |\mathbf{v}_{r,k}^{(p)\dagger}\mathbf{h}_{0r}|^2 P_P}{N_0}\right),\ k \in \mathcal{S}_1. \tag{10}$$

In Phase Two, since MRC is used, the effective SNR at PR equals to the sum of the SNRs from all the secondary relays. Based on Eqn. (7), in the subslot when ST_k is transmitting, the achievable rate of the cooperative link is given by

$$R_k^{(SP)} = \log_2\left(1 + \sum_{r\in\mathcal{R}} \frac{|\mathbf{h}_{r0}\mathbf{u}_{r,k}^{(p)}|^2 P_r}{N_0}\right),\ k \in \mathcal{S}_2. \tag{11}$$

Moreover, denote the channel gain from PT to PR as h_P, in the trivial case when the secondary cooperation is not applied, the rate of the direct transmission from PT to PR is

$$R_{dir} = \log_2\left(1 + \frac{|h_P|^2 P_P}{N_0}\right). \tag{12}$$

2) Secondary Link: For simplicity, it is assumed that for each secondary pair, ST will adopt a fixed power level for transmitting the secondary data, while the power P_r used for relaying the primary data is adaptive. Denote $P_k^{(s)}$ to be the power used by ST_k for secondary data transmission. Based on Eqn. (6) and Eqn. (9), the transmission rate of secondary link (ST_k, SR_k) in the two phases can be unified as

$$R_k^{(s)} = \log_2\left(1 + \frac{|\mathbf{v}_k^{(s)\dagger}\mathbf{H}_{kk}\mathbf{u}_k^{(s)}|^2 P_k^{(s)}}{N_0}\right) \qquad \forall k \in \mathcal{R}. \tag{13}$$

Specifically in Phase One, for each ST_k, $\mathbf{v}_k^{(s)}$ can be chosen to satisfy $\mathbf{v}_k^{(s)\dagger}\mathbf{h}_{0k} = 0$. Then $\mathbf{u}_k^{(s)}$ can be chosen in the same direction as $\mathbf{v}_k^{(s)\dagger}\mathbf{H}_{kk}$ to maximize $|\mathbf{v}_k^{(s)\dagger}\mathbf{H}_{kk}\mathbf{u}_k^{(s)}|^2$. Accordingly, $\mathbf{v}_{r,k}^{(p)\dagger}$ can be resolved for each relay r given $\mathbf{u}_k^{(s)}$. In Phase Two, $\mathbf{u}_k^{(s)}$ is chosen to let $\mathbf{h}_{k0}\mathbf{u}_k^{(s)} = 0$. Since the P_r's cannot be determined in priori in Eqn. (7), we will align each $\mathbf{H}_{rk}\mathbf{u}_{r,k}^{(p)}$ in the same direction that is orthogonal to $\mathbf{H}_{kk}\mathbf{u}_k^{(s)}$. As a result, $\mathbf{u}_{r,k}^{(p)}$ can be resolved to satisfy $(\mathbf{H}_{kk}\mathbf{u}_k^{(s)})^\dagger\mathbf{H}_{rk}\mathbf{u}_{r,k}^{(p)} = 0$. Also given $\mathbf{u}_k^{(s)}$, $\mathbf{v}_k^{(s)}$ is computed to maximize $|\mathbf{v}_k^{(s)\dagger}\mathbf{H}_{kk}\mathbf{u}_k^{(s)}|^2$.

To conclude, given the sets of relays $\mathcal{S}_1$, $\mathcal{S}_2$ and the channel matrices, all the encoding/decoding vectors can be determined, thus the primary link rates $R_k^{(PS)}$ and $R_k^{(SP)}$ are resolved. Further, all the relay pairs can locally calculate the rate $R_k^{(s)}$ for its own transmission.

C. Problem Formulation

In this paper, the objective of the primary link is to maximize its utility, termed as throughput, over the different combinations of relay sets $\mathcal{S}_1$, $\mathcal{S}_2$, and the time length scale α of the two phases. The throughput for cooperative communication is the minimum of the throughput in the two phases:

$$R_{coop} = \min\{\sum_{i\in\mathcal{S}_1} T_i^{(1)} R_i^{(PS)}, \sum_{i\in\mathcal{S}_2} T_i^{(2)} R_i^{(SP)}\}. \tag{14}$$

So the primary rate R_P in this frame duration is

$$R_P = \begin{cases} R_{dir} & \alpha = 1 \\ R_{coop} & 0 < \alpha < 1. \end{cases} \tag{15}$$

Thus the primary link aims at solving the following *primary utility maximization problem*:

$$\begin{array}{ll} \max_{\alpha,\mathcal{S}_1,\mathcal{S}_2,T_i^{(1)},T_i^{(2)},P_r} & R_P, \\ \text{Subject to:} & \sum_{i\in\mathcal{S}_1} T_i^{(1)} = \alpha T, \\ & \sum_{i\in\mathcal{S}_2} T_i^{(2)} = (1-\alpha)T, \\ & 0 \le P_r \le P_r^{max}, \forall r \in \mathcal{R}, \\ & \mathcal{S}_1, \mathcal{S}_2 \subseteq \mathcal{S} \text{ and } \mathcal{S}_1 \cap \mathcal{S}_2 = \emptyset, \\ & 0 < \alpha \le 1. \end{array} \tag{16}$$

The first and second constraint limits the total length of the subslots in Phase One and Phase Two. The third constraint means the transmission power for relaying the primary signal of each relay r is bounded by P_r^{max}, which is given as the power budget for relaying. Due to the non-cooperative nature of the secondary network, P_r's are determined as the result of the competition between the SUs. This will be illustrated in detail in Section V. The set $\mathcal{R} = \mathcal{S}_1 \cup \mathcal{S}_2$ is determined once the sets $\mathcal{S}_1$ and $\mathcal{S}_2$ are known.

D. Beyond Two Antennas

In the general case of multiple antennas per SU in MIMO-CCRN, the principle for relaying the primary data remains the same. Besides, multiple concurrent data streams can be transmitted between a secondary pair by using spatial multiplexing. For example, when all the SUs are equipped with three antennas in Fig. 3, ST_1 can simultaneously transmit two streams for its own traffic to SR_1 in its subslot, the same is true for ST_2, ST_3 and ST_4 in their respective subslots. Generally, to make the streams decodable, the number of concurrent streams a node can transmit should be no more than its DoF, which is given by the number of antennas it has. Symmetrically, the number of streams a receiver can simultaneously receive (including the interfering streams) is also limited by its DoF [10]. This fact characterizes the feature that MIMO increases the link capacity linearly with the number of antennas.

Guided by the above principle, we discuss the feasibility of link-layer stream scheduling for the secondary network. The details of computing the beamforming vectors are omitted here. We define the number of antennas of ST_i and SR_i as Ant_{ST_i} and Ant_{SR_i} respectively. We assume PT and PR have one antenna each and a relay set $\mathcal{R}$ is given. In Phase One, when ST_k is scheduled to transmit in its subslot, it should guarantee the number of streams other relays receive does not exceed their DoFs. Therefore, the number of secondary streams it can send is $str_k = \min_{\forall r\in\mathcal{R}}\{Ant_{ST_k}, Ant_r - 1\}$. The decrease by one of Ant_r is due to the reception of the primary stream. Similarly in Phase Two, in the subslot for ST_k to transmit, ST_k should relay one primary stream, while SR_k is receiving an interfering primary stream. Thus $str_k = \min\{Ant_{ST_k} - 1, Ant_{SR_k} - 1\}$ streams can be sent by ST_k for its own traffic.

V. GAME THEORY ANALYSIS

In this section, we analyze our problem under a typical two-stage Stackelberg game framework. We will resolve the unique Nash Equlibrium (NE) for the secondary power control game, and maximize the primary link's utility based on the NE.

A. Secondary Power Control Game

In the context of spectrum leasing in CCRN, the primary and secondary networks are intrinsically non-cooperative. It is best to analyze the problem under the framework of Stackelberg game [1], [2]. The PU owns the spectrum band and thus is the leader possessing a higher priority in choosing the optimal relay sets and parameters. The secondary pairs in $\mathcal{S}$ are the followers competing with each other to decide the best strategy to share the spectrum. All the entities are rational and selfish aiming to maximize their own utilities. Guided by the idea of backward induction [1], [2], it is necessary to decompose the problem so that the optimal $T_i^{(1)}$, $T_i^{(2)}$ and P_r in (16) can be obtained if $\mathcal{S}_1$, $\mathcal{S}_2$ and α are given. This is achieved by finding a unique NE for the *secondary power control game*. Then based on the knowledge of the NE, the primary links determines the best relay sets $\mathcal{S}_1$, $\mathcal{S}_2$ and the parameter α.

In MIMO-CCRN, secondary pairs compete with each other for the channel access, in terms of the durations of the subslots in Phase One and Phase Two. For each secondary pair $k \in \mathcal{R}$, the utility function is defined as the difference between the achievable throughput and the cost of energy used in this frame duration as in [1], which is then:

$$u_k^{(s)} = T_k^{(i)}(R_k^{(s)} - wP_k^{(s)}) - wP_k(1-\alpha)T, \ \forall k \in \mathcal{S}_i, \tag{17}$$

where $R_k^{(s)}$ is determined by Eqn. (13), w is the cost per unit transmission energy and P_k is the power used for relaying adopted by the secondary pair k.

Meanwhile, we let $T_k^{(1)}$ and $T_k^{(2)}$ be proportional to relay k's consumed energy for relaying, which is represented as

$$T_k^{(i)} = c_i \cdot \frac{P_k}{\sum_{j\in\mathcal{S}_i} P_j}, \tag{18}$$

where $c_i = \alpha T$ for $k \in \mathcal{S}_1$ and $c_i = (1-\alpha)T$ for $k \in \mathcal{S}_2$. We can see that the utility function for each secondary pair is a function of their transmission power used for the primary signal relaying, therefore a *secondary power control game* can be formulated. Secondary pairs in each set $\mathcal{S}_i$ being the *players*, form a non-cooperative power selection game and compete in the same set to maximize its own utility. The *strategy space* is the power $\mathcal{P} = [\mathbf{P}_k] : 0 \leq P_k \leq P_k^{max}$. The best strategy can be resolved for each relay when the NE is achieved. Based on Eqn. (17) and (18) and using $\hat{R}_k^{(s)}$ to replace $R_k^{(s)} - wP_k^{(s)}$, the utility for the secondary pair k in $\mathcal{S}_1$ is

$$u_k^{(s)} = \alpha T \cdot \frac{P_k}{\sum_{i \in \mathcal{S}_1} P_i} \hat{R}_k^{(s)} - wP_k(1-\alpha)T, \ k \in \mathcal{S}_1. \quad (19)$$

In this section, we analyze the NE for the secondary pairs in $\mathcal{S}_1$ based on Eqn. (19) in detail. Similar methods can be applied to the game among the relays in set $\mathcal{S}_2$. We will first prove the existence and uniqueness of the Nash Equilibrium.

Theorem 1: A Nash Equilibrium exists in the secondary power control game.

Proof: Note that Eqn. (19) has similar form as the utility function defined in [2] (Eqn. (7)). Using the same method, we can first prove that $\mathbf{P}_k$ is a nonempty, convex and compact subset of the Euclidean space $\Re$, then prove that $u_k^{(s)}$ is continuous and concave in P_k. A Nash Equilibrium then exists if these two conditions satisfy. We omit the details due to the space limit, and let interested readers refer to [2]. ■

To analyze the uniqueness of the equilibrium, we should refer to the best response function of player k given the power selection of other players. Since the utility function $u_k^{(s)}$ is concave, the best response is achieved when the first derivative of $u_k^{(s)}$ with P_k equals to 0, as

$$\frac{\partial u_k^{(s)}}{\partial P_k} = \frac{\alpha T \hat{R}_k^{(s)} \sum_{i \in \mathcal{S}_1, i \neq k} P_i}{(\sum_{i \in \mathcal{S}_1} P_i)^2} - w(1-\alpha)T = 0. \quad (20)$$

Solving Eqn. (20) and eliminating the trivial cases when the power is negative or exceeds P_k^{max}, the best response function is

$$r_k(\mathbf{P}) = \sqrt{\frac{\alpha \hat{R}_k^{(s)} \sum_{i \in \mathcal{S}_1, i \neq k} P_i}{w(1-\alpha)}} - \sum_{i \in \mathcal{S}_1, i \neq k} P_i, \quad (21)$$

$\forall k \in \mathcal{S}_1$, with the following constraint:

$$0 \leq r_k(\mathbf{P}) \leq P_k^{max}. \quad (22)$$

Theorem 2: The secondary power control game has a unique Nash Equilibrium.

Proof: This amounts to proving that the system represented by the equation set (21) has a unique solution. Solving the equation set (21) consisting of $|\mathcal{S}_1|$ equations, the resulting relaying power for SR$_k$ when $k \in \mathcal{S}_1$ is

$$P_k^* = \frac{\alpha}{1-\alpha} a_k, \quad (23)$$

where

$$a_k = \frac{(|\mathcal{S}_1| - 1)}{w \sum_{i \in \mathcal{S}_1} \frac{1}{\hat{R}_i^{(s)}}} \left(1 - \frac{|\mathcal{S}_1| - 1}{\hat{R}_k^{(s)} \sum_{i \in \mathcal{S}_1} \frac{1}{\hat{R}_i^{(s)}}}\right).$$

We can see that the resulting P_k^* is unique for each relay in $\mathcal{S}_1$, which is the transmitting power it will adopt to relay the primary data when the equilibrium is reached. ■

Similarly, we can prove that the NE point also exists and is unique for the secondary power control game among the secondary relay pairs in the set $\mathcal{S}_2$. The relaying power for each pair should be chosen as

$$P_k^* = b_k = \frac{(|\mathcal{S}_2| - 1)}{w \sum_{i \in \mathcal{S}_2} \frac{1}{\hat{R}_i^{(s)}}} \left(1 - \frac{|\mathcal{S}_2| - 1}{\hat{R}_k^{(s)} \sum_{i \in \mathcal{S}_2} \frac{1}{\hat{R}_i^{(s)}}}\right). \quad (24)$$

Note that P_k^* is independent of α for relay pairs which belong to $\mathcal{S}_2$. In Section V, a unique NE point is found for all the simulations for each set $\mathcal{S}_1$ and $\mathcal{S}_2$.

B. Maximizing the Primary Link's Utility

Based on the analytical result of the secondary power control game, as the leader of the Stackelberg game, the primary link can resolve the best system parameters to solve the formulated *primary utility maximization problem.*

The relaying power for each relay can be obtained according to Eqn. (23) and (24), where a_k and b_k are known if $\mathcal{S}_1$, $\mathcal{S}_2$ and the secondary link rates are given. To resolve the optimal α, we can substitute (23) and (24) into (11), the resulting link rate in Phase Two of MIMO-CCRN is

$$R_i^{(SP)} = \log_2(1 + A_i \cdot \frac{\alpha}{1-\alpha} + B_i), i \in \mathcal{S}_2, \quad (25)$$

where $A_i = \sum_{k \in \mathcal{S}_1} \frac{|\mathbf{h}_{r0} \mathbf{u}_{r,i}^{(p)}|^2 \cdot a_k}{N_0}$, $B_i = \sum_{k \in \mathcal{S}_2} \frac{|\mathbf{h}_{r0} \mathbf{u}_{r,i}^{(p)}|^2 \cdot b_k}{N_0}$. r refers to SR$_k$ when $k \in \mathcal{S}_1$, and ST$_k$ when $k \in \mathcal{S}_2$.

Moreover, it has been proved that in two-phase cooperative communication [1], the throughput is maximized when the downlink throughput equals to the uplink throughput. In our problem, to maximize the PU's throughput, we should have

$$\sum_{k \in \mathcal{S}_1} T_k^{(1)} R_k^{(PS)} = \sum_{k \in \mathcal{S}_2} T_k^{(2)} R_k^{(SP)}. \quad (26)$$

Expanding Eqn. (26) based on (18) and (25), we have

$$\sum_{k \in \mathcal{S}_2} D_k \log_2(1 + A_k \cdot \frac{\alpha^*}{1-\alpha^*} + B_k) = C \cdot \frac{\alpha^*}{1-\alpha^*}, \quad (27)$$

where $C = \frac{\sum_{k \in \mathcal{S}_1} P_k^* R_k^{(PS)}}{\sum_{k \in \mathcal{S}_1} P_k^*} = \frac{\sum_{k \in \mathcal{S}_1} a_k R_k^{(PS)}}{\sum_{k \in \mathcal{S}_1} a_k}$ and $D_k = \frac{P_k^*}{\sum_{i \in \mathcal{S}_2} P_i^*} = \frac{b_k}{\sum_{i \in \mathcal{S}_2} b_i}$. α^* in the above formula is the optimal α. It is easy to see that $\frac{\alpha^*}{1-\alpha^*}$ is the x-coordinate of the intersection point between the summation of a set of log functions and a straight line passing through the origin. Thus, any one-directional search method can be applied to give the value of α^* efficiently.

Based on the the above, and given $\mathcal{S}_1$ and $\mathcal{S}_2$, α^* can be resolved, which determines the optimal durations of the two phases to maximize the throughput of the primary link. In a practical implementation, the secondary network measures the channel coefficient matrices $\mathbf{h}_{0r}$, $\mathbf{h}_{r0}$, $\mathbf{H}_{ir}$ and $\mathbf{H}_{ri}$, while PR measures h_p. Then PT periodically collects this data. From the universal set of the relay pairs $\mathcal{S}$, the PT can enumerate all the possible sets $\mathcal{S}_1$ and $\mathcal{S}_2$ which satisfy the criteria (22). From all the possible sets, the one that maximizes the primary link's utility can be selected. The information of the optimal set $\mathcal{R}$,

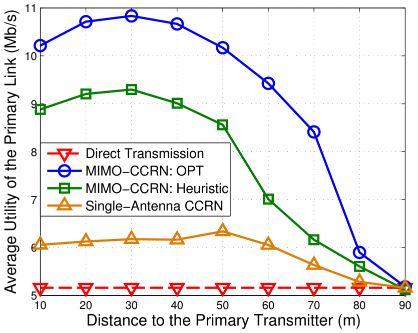

Fig. 4. Primary link's utility for different schemes.

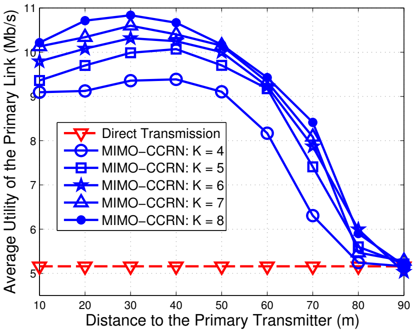

Fig. 5. Impact of the number of relays.

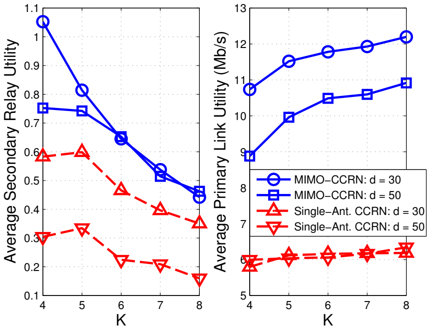

Fig. 6. The utilities achieved by PUs and SUs.

α^* and beam-forming vectors will be piggybacked to the SUs. The secondary pairs being selected as the relays can calculate the best relaying power in a distributed fashion.

VI. PERFORMANCE EVALUATION

In this section, we evaluate the impact of different system characteristics on the performance of MIMO-CCRN. We consider a topology where there exists one primary link and $K = |\mathcal{S}|$ secondary pairs. Each SU in the system (ST and SR) is equipped with two antennas. The distance between PT and PR, each with a single antenna, is 100 meters. To reduce the number of model parameters, we adopt a simple geometrical model where the SUs are all located at approximately the same distance d $(0 < d < 100)$ from the PT and $100 - d$ from the PR as in [1], [2]. The channel model is decomposed into a large-scale component with path loss exponent $\eta = 3$, and a small-scale Rayleigh fading component with $\sigma = 1$. Thus the average channel gain from PT to each antenna of the SUs is $1/d^{\eta}$, and from each antenna of the SUs to PR is $1/(100-d)^{\eta}$. For the secondary network, we assume the average channel gain between ST_i and ST_j/SR_j is $1/40^{\eta}$ for $i = j$ and $1/120^{\eta}$ for $i \neq j$. According to [21], the bandwidth of the primary spectrum is set to 6 MHz and thermal noise level is -129.5 dBm. The transmitting power of PT, P_p, is fixed to a value such that the average SNR of the primary link is 0 dB. The cost per unit transmission energy is $w = 10$. Each point in the figures is averaged over 300 independent frame durations.

Figure 4 shows the average utility of the primary link, in terms of the throughput under different schemes versus the distance d. We use *"MIMO-CCRN: OPT"* to represent the performance of MIMO-CCRN through exhaustive search of the best relay set. To reduce the complexity, we restrict our search to the sets $\mathcal{S}(i,j), 0 \leq i,j \leq K$. $\mathcal{S}(i,j)$ is the relay set constructed by including the top i SRs and top j STs with best downlink channel gains $|h_{0r}|^2$ into $\mathcal{R}$ (also ST and SR are not from the same pair). The reason is to greedily enhance the downlink capacity, which is the bottleneck of our cooperative communication. The performance given by this heuristic algorithm is denoted as *"MIMO-CCRN: Heuristic"*. In addition, we use *"Single-Antenna CCRN"* to denote the CCRN scheme proposed in [1], which also aims at maximizing the PU's throughput. It assumes that each SU is equipped with a single antenna. For fair comparison, both schemes adopts the same settings stated above, and the power budget for SUs are all set to $P_r^{max} = P_p$. In MIMO-CCRN, we assume the target rate $R_k^{(s)}$ of each secondary pair is 5 Mb/s. The number of secondary pairs is $K = 8$. Finally *"Direct Transmission"* gives the primary link's throughput without SU cooperation.

From the figure, we can see that by exploiting the SU cooperation with MIMO capability, MIMO-CCRN significantly improves the throughput of the primary link by up to 110% compared with direct transmission. Also, MIMO-CCRN outperforms the Single-Antenna CCRN by up to 75%. This is due to the following two reasons: (i) Secondary relays equipped with multiple antennas achieve a stronger beam-forming in receiving and forwarding the PU's data; (ii) By exploiting the spatial domain, no dedicated fraction of time is allocated to the SUs, thus the overhead for the PU's transmission is reduced. Moreover the primary link's throughput reaches a peak when d is around 30, which is the location that best balances the uplink/downlink capacity. Also our heuristic algorithm gives a fairly acceptable performance, which is about 85% of the optimal PU's throughput for most of the points.

Figure 5 shows the impact of the number of secondary pairs K on the primary link's throughput. We can see when K increases, the primary link's throughput improves. For example, when $d = 30$, the PU's throughput increases from 9.36 Mb/s to 10.83 Mb/s as K changes from 4 to 8. This is because when K becomes larger, there will be more choices for the primary link to choose the secondary relay sets $\mathcal{S}_1$ and $\mathcal{S}_2$, thus potentially finding better relay sets to enhance its throughput.

TABLE I
OPTIMAL α^* VERSUS THE DISTANCE d.

d	10	20	30	40	50	60	70	80
α^*	0.21	0.32	0.43	0.53	0.64	0.73	0.81	0.83

Table I depicts the relationship between the optimal parameter α^* and the distance d. We set $K = 8$. As d increases, the downlink capacity from PT to the secondary relays tends to decrease while the uplink capacity from the relays to the PR tends to increase. Therefore, to achieve the optimal overall throughput, the time duration needed for the first phase will increase, which leads to a larger α^*.

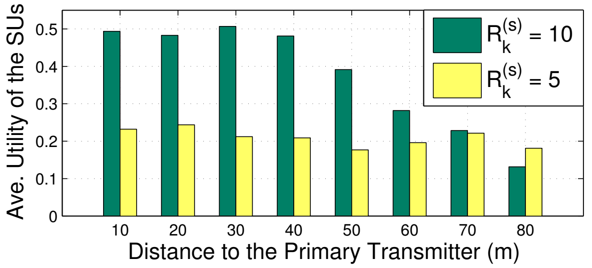

Fig. 7. Average utility of the secondary pairs.

The utilities achieved by the SUs are studied next. Fig. 6 shows the comparison of the utilities achieved by the PUs and SUs in MIMO-CCRN and Single-Antenna CCRN for different K. We set $R_k^{(s)}$ of each secondary pair to be 10 Mb/s in MIMO-CCRN, and the power budget P_r^{max} of SUs in both schemes to be the same. For the SUs, since the settings for all the secondary pairs are homogeneous, we measure the utility achieved by a single pair averaged over 300 frame durations. The left part of the figure displays the SU results. As we can see, in both $d = 30$ and $d = 50$ cases, MIMO-CCRN gives a larger utility to the SUs than Single-Antenna CCRN. The reason is that by exploiting the additional spatial domain in MIMO-CCRN, SUs can be scheduled to transmit their own data throughout the frame duration, instead of being confined to a dedicated time fraction in Single-Antenna CCRN scheme. Moreover, as K increases, more secondary pairs are participating in the competition for the spectrum, which results in a decrease in average utility gained by a single secondary pair. This phenomenon conforms to the basic economic principles. The right part of Fig. 6 shows the corresponding average utility achieved by the primary link for each simulation point. Similar with what is observed in Fig. 4, in MIMO-CCRN the primary link also enjoys a higher utility than it does in Single-Antenna CCRN, which verifies that MIMO-CCRN realizes a stronger win-win situation for PUs and SUs. When K increases, the utility gained by the primary link increases as in Fig. 5.

Fig. 7 provides a closer look at the utilities achieved by the SUs. There are $K = 8$ secondary pairs in the network. We modify the topology so that they are placed at $d = 10, 20, 30, \ldots, 80$, one pair for each location. Fig. 7 shows the average utility achieved by each pair for different secondary transmission rates $R_k^{(s)}$ of SUs. We can see that when $R_k^{(s)}$ increases from 5 Mb/s to 10 Mb/s, the average utility of SUs increases. This is because the gain obtained by the larger data rate overrides the cost of the energy used for transmission, as in Eqn. (17). Moreover according to Eqn. (23) and (24), the relaying power P_k for each secondary pair will increase, which potentially improves the uplink capacity from the relays to the PR. Therefore when $R_k^{(s)}$ is 10 Mb/s, the secondary pairs closer to the PT have a higher priority to be chosen as relays to improve the overall achievable rate of the cooperative communication. We can see that they enjoy higher average utilities compared to the SUs further from the PT.

VII. CONCLUSION

This work represents a novel design called MIMO-CCRN to leverage MIMO in cooperative cognitive radio networks. It allows the SUs to cooperatively relay the traffic for the PUs while simultaneously transmitting their own traffic. We design the system architecture by considering both the temporal and spatial domain to improve spectrum efficiency. By formulating MIMO-CCRN as a Stackelberg game, we analytically derive the optimal uplink/downlink durations and relay set selection based on the Nash Equilibrium. Simulation results show that both the primary and the secondary network achieve higher utility in MIMO-CCRN than in the conventional schemes.

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