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Efficient Cooperative MIMO Paradigms for Cognitive Radio Networks

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Abstract

This paper investigates the benefits that cooperative communication brings to cognitive radio networks. We focus on cooperative Multiple Input Multiple Output (MIMO) technology, where multiple distributed single-antenna secondary users cooperate on data transmission and reception. Three cooperative MIMO paradigms are proposed to maximize the diversity gain and significantly improve the performance of overlay, underlay and interweave systems. In the paradigm for overlay systems the secondary users can assist (relay) the primary transmissions even when they are far away from the primary users. In the paradigm for underlay systems the secondary users can share the primary users' frequency resources without any knowledge about the primary users' signals. The transmitted spectral density of the secondary users falls below the noise floor at the primary receivers to meet the strict interference constraint in cognitive radio networks. In the paradigm for interweave systems, secondary users can use cooperative beamforming to avoid the interference at the primary users while still achieving high diversity gain for improved system performance. Numerical and experimental results are provided in order to discuss the advantages and limits of the proposed paradigms.

Keywords: Cognitive radio networks, cooperative communication, MIMO technology, beamforming, energy efficient, system optimization

1 Introduction

Cognitive radio is a promising paradigm in wireless communication that enables efficient use of frequency resources by allowing the coexistence of licensed primary users (PUs) and unlicensed secondary users (SUs) in the same frequency band. The solution is achieved by endowing the radio nodes with "cognitive capabilities," e.g., the ability to sense the electromagnetic environment, make short term predictions, and react consequently by adapting transmission parameters (e.g., operating spectrum, modulation, and transmission power) in order to optimize the usage of the available resources [1]. Three basic approaches have been considered to allow concurrent communications: spectrum overlay, underlay, and interweave [2]. In an overlay system, the SUs allocate part of their power for secondary transmissions and the remainder to assist (relay) the primary transmission. SUs somehow facilitate the PUs, for example, by means of advanced coding or cooperative techniques based on the knowledge of the PUs' message and/or codebook at the cognitive transmissions without capacity penalties. In an underlay system, the SUs are allowed to share frequency resources with the PUs without any knowledge about the PUs' signals, under the strict constraint that the transmitted spectral density of the SUs falls below the noise floor at the primary receivers. Interweave system is an opportunistic communication paradigm, where SUs are able to sense and learn from the environment in a nonintrusive manner. The system is allowed to transmit over a multidimensional space, whose coordinates represent time slots, frequency bins, and possible angles. The goal of the interweave system is to find out the most appropriate transmission strategy by exploring all available degrees of freedom under the constraint of inducing a limited interference, or no interference at all, to the PUs.

Relaying primary traffic by SUs for the overlay systems is investigated in [3], where a SU assists the primary transmission from one PU (the source) to another PU (the intended destination) through optimizing transmission parameters towards the goal of maximizing the data rate of the primary receiver. The limitation of [3] is that the assistant SU has to be in the convenient location, typically halfway between the source and destination. In [1, 4, 5], SUs in the underlay systems make decisions in their own interest by maximizing their utility function while influenced by the other players' decisions . These works are based on a game theoretical approach. The main drawback of this approach is that the maximization of the game utility function represents an incentive to reduce the interference at the PUs' receiver, but not a guarantee that the aggregated interference generated by SUs is maintained below a certain threshold, especially in the scenarios that the spatial reuse is most challenging, for example, when PUs' receivers are passive or when SUs' transmitter are very close to PUs' receivers [6]. In [1, 7, 8], beamforming is used for the interweave systems to reduce and limit the interference at PUs. These beamforming approaches utilize the multiple antennas in Multiple Input Multiple Output (MIMO) radio systems. MIMO radio systems employ multiple transmission and reception antennas to provide extremely high spectral efficiencies by simultaneously transmitting multiple data streams in the same channel. The gains induced by MIMO technology can also be used in wireless network for improving system performance, e.g. raising data rate, reducing error rate, extending communication range. However, it is unrealistic in many cases to have the terminal devices equipped with multiple antennas due to the size and cost of the devices. Cooperative/Virtual MIMO technique is a proved solution to this problem [9, 10]. In cooperative MIMO technique, multiple single-antenna nodes cooperate on data transmission and reception to achieve the same spectral efficiencies that the MIMO nodes provide.

In this paper, we investigate the advantages that the cooperative MIMO technology brings to cognitive radio networks. Three cooperative MIMO paradigms are proposed to maximize the diversity gain and significantly improve the performance of overlay, underlay and interweave systems. In the paradigm for overlay systems the secondary users can assist (relay) the primary transmissions even when they are far away from the primary users. In the paradigm for underlay systems the secondary users can share the primary users' frequency resources without any knowledge about the primary users' signals while meet the strict interference constraint that the transmitted spectral density of the secondary users falls below the noise floor at the primary receivers. In the paradigm for interweave systems, secondary users can use cooperative beamforming to avoid the interference at the primary users while still achieving high diversity gain for improving the system performance. Numerical and experimental results are provided in order to discuss the advantages and limits of the proposed paradigms. This work is the extension of [11]. By adding the cooperative MIMO paradigm for interweave systems (our most recent result) and more analysis and experiments, this paper is a completed version which investigates cooperative MIMO paradigms for all of overlay, underlay and interweave systems in cognitive radio networks.

The remaining of this paper is organized as follows. Section 2 introduces the cooperative MIMO network model, cooperative communication schemes and the energy model. Section 3, 4 and 5 elaborate the proposed cooperative overlay, underlay and interweave MIMO paradigms for cognitive radio networks. The numerical analysis and experiment results are given in Section 6. Finally, Section 7 concludes the whole paper.

2 Cooperative MIMO Network Model, Cooperative Communication Schemes and Energy Model

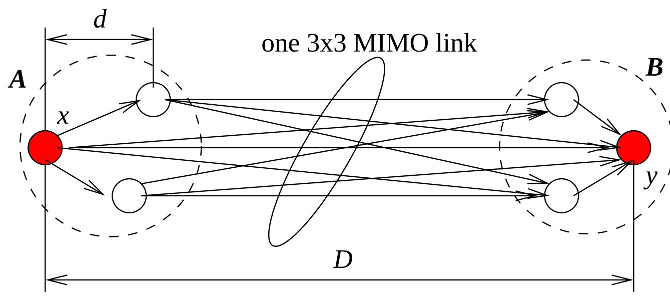
MIMO with multiple-node cooperation allows multiple single-antenna nodes cooperate on data transmission and reception. Cooperative transmission in its basic forms refers to the information theoretic model of the relay channel. Performance advantages achievable from collaboration arise from the diversity gain obtained from the multiple paths between the multiple nodes in transmission side and those in reception side. In the context of cognitive radio networks, cooperative MIMO techniques is used with SUs in order to avoid interference, reduce energy consumption, extend transmission range, and reduce error rate.

2.1 Cooperative network model

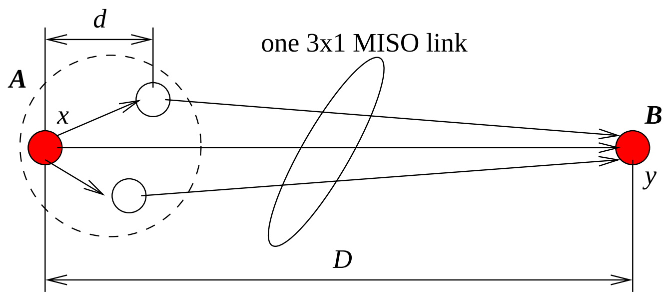
Let $G = (V, E)$ be the network of SU nodes, where V is the set of SU nodes equipped with single-antenna radio. For any pair of nodes u and v, the edge $(u, v) \in E$ if u and v are in their communication range with each other. A cooperative MIMO network (CoMIMONet) is defined on G. A d-clustering of V is a node disjoint division of V, where the distance between two SU nodes in a cluster is up to d ($d \leq r$) and r is the communication range. Let A and B be two d-clusters and there are mt nodes in A and mr nodes in B. If the largest distance between a node of A and a node of B is up to D (usually, $D >> d$), a D-$mt \times mr$ cooperative MIMO transmission link is defined between A and B: the nodes in A cooperate on transmission in which node i in A uses its antenna as the i-th antenna and the nodes in B cooperate on reception in which node j in B uses its antenna as the j-th antenna cooperating on the reception. According to $mt = mr = 1$, $mt > 1$ and $mr = 1$, $mt = 1$ and $mr > 1$, $mt > 1$ and $mr > 1$, the cooperative link is called Single Input Single Output (SISO) link, Multiple Input Single Output (MISO) link, Single Input Multiple Output (SIMO) link and MIMO link, respectively. A CoMIMONet can be represented by an undirected graph $G_{MIMO} = (V_{MIMO}, E_{MIMO})$, where V_{MIMO} is the set of the clusters and E_{MIMO} is the set of edges. An edge $(A, B) \in E_{MIMO}$ if and only if A and $B \in V_{MIMO}$ and there is a cooperative MIMO link defined between A and B. In the rest of the paper, the clusters are also called cooperative MIMO nodes, and the SU nodes in a cooperative MIMO node are called elementary nodes. In each cluster there is a special elementary node called the head node. The head node retains information of other elementary nodes such as ID and battery power level, and the other elementary nodes retain the information about the head. The head nodes can control and synchronize the cooperative transmission and reception. All head nodes form a spanning tree which is used as a routing backbone and it paths are used for data relay. The clusters and the routing backbone are reconfigurable. Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) is used to avoid the communication collisions at the link layer. More details for CoMIMONet formation/reconfiguration and routing protocol can be found in [9].

2.2 Cooperative communication schemes

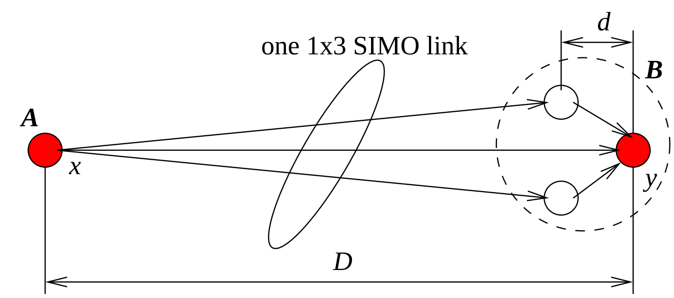
In CoMIMONet, the data transmitted from the source node to the final destination node usually takes multiple hops. This subsection discusses the cooperative communication schemes for one hop in the data relay path. Suppose there are mt cooperative SU nodes in transmission cluster A and mr cooperative SU nodes in reception cluster B, and the head node x in A transmits the data to the head node y in B. The cooperative data communication between x and y consists of intra data communication inside cluster A and cluster B and inter data communication between A and B, as



(a) Cooperative MIMO Scheme



(b) Cooperative MISO Scheme



(c) Cooperative SIMO Scheme

Figure 1: Cooperative Communication Schemes

shown in Figure 1. The MIMO, MISO, and SIMO communication schemes are described as follows, where the MISO and SIMO schemes are special cases of the MIMO scheme.

MIMO scheme (Figure 1 (a)) ($mt > 1$ and $mr > 1$)

> **Step 1** (Intra/Local transmission at A) Node x broadcasts the source data to other local nodes in A. After this step, each node in A has the source data.
> **Step 2** (Transmission between A and B with a $mt \times mr$ cooperative MIMO link): Each node i in A acts as the i-th antenna and encodes the source data using the MIMO code system. All mt nodes in A broadcast the encoded sequence to the mr nodes in B simultaneously.
> **Step 3** (Intra/Local transmission at B): Each node in B transmits the received data using different time slots to y. y decodes the received data back to the source data based on the MIMO code system.

MISO scheme (Figure 1 (b)) ($mt > 1$ and $mr = 1$)

> **Step 1** (Intra/Local transmission at A) Node x broadcasts the source data to other local nodes in A. After this step, each node in A has the source data.

Step 2 (Transmission between A and B with a $mt \times 1$ cooperative MISO link): Each node i in A acts as the i-th antenna and encodes the source data using the MISO code system. All mt nodes in A broadcast the encoded sequence to the nodes of y in B simultaneously. The head of y decodes the received data back to the source data based on the MISO code system.

SIMO scheme (Figure 1 (c)) ($mt = 1$ and $mr > 1$)

Step 1 (Transmission between A and B with a $1 \times mr$ cooperative SIMO link): The node x with the source data in A broadcasts the source data sequence to the mr nodes in B.
Step 2 (Intra/Local transmission at B): Each node in B transmits the received data using different time slots to y. y decodes the received data back to the source data.

2.3 Energy model

In this paper, the MIMO systems are referring to the ones coded with space-time block codes (such as Alamouti code) and a flat Rayleigh fading channel as those used in [10]. The path loss is modeled as a power fall off proportional to the distance squared. Given bandwidth B and constellation size b (bits per symbol), bB bits can be transmitted per second. We consider a variable-rate system, where b can be different at different cooperative links. In order to keep the model from being over-complicated, signal processing blocks (source coding, pulse-shaping, digital modulation and channel coding) are intentionally omitted. The methodology used here can be extended to use other MIMO codes and include the signal processing blocks.

The following formulas used for evaluating energy can be found in [10, 12]. For local transmission, a κ-th power path loss with AWGN is assumed. Let e^{Lt} denote the energy cost per bit at each elementary node for local/intra data transmission. It can be presented to two parts: e^{Lt}_{PA} is the energy consumption per bit for the power amplifiers, and e^{Lt}_{C} is the the energy consumption per bit for the circuit. Let e^{Lr} denote the energy cost per bit at each elementary node for local/intra data reception. Note that the energy for the reception that is consumed only in the circuit. Since usually the long-haul distance D between the cooperative transmission cluster and reception cluster is much larger than the diameter d of the clusters, we assume that the long-haul transmission distance is the same between each pair of the transmission node in the transmission side and reception node in the reception side in a cooperative link. Let $e^{MIMOt}(mt, mr)$ denote the energy cost per bit at each elementary node for data transmission in long-haul $mt \times mr$ cooperative MIMO link. It can be presented to two parts: e^{MIMOt}_{PA} is the energy consumption per bit for the power amplifiers, and e^{MIMOt}_{C} is the the energy consumption per bit for the circuit. Let e^{MIMOr} denote the energy cost per bit at each elementary node for data reception at each receiving node in cooperative link. In the following formulas, p, B, d, D, b, and n represent the bit error rate (BER), bandwidth, diameter of virtual MIMO node, length of virtual MIMO link, constellation size, and information size in transmission, respectively, and P_{ct}, P_{cr}, P_{syn} represent the energy consumptions in circuits for transmission, reception and synchronization.

1. Energy consumption per bit at each elementary node for local/intra data transmission

$$\begin{aligned} e^{Lt} &= e^{Lt}_{PA} + e^{Lt}_{C}, \quad where \\ e^{Lt}_{PA} &= \frac{4}{3}(1+\alpha)\frac{2^b - 1}{b} \ln \frac{4(1-2^{-b/2})}{bp} G_d N_f \sigma^2, and \\ e^{Lt}_{C} &= P_{ct}/(bB) + P_{syn}T_{tr}/n \end{aligned} \tag{1}$$

2. Energy consumption per bit at each elementary node for local/intra reception

$$e^{Lr} = P_{cr}/(bB) + P_{syn}T_{tr}/n \tag{2}$$

3. Energy consumption per bit at each elementary node for data transmission in long-haul $mt \times mr$ cooperative MIMO link

$$e^{MIMOt}(mt, mr) = e^{MIMOt}_{PA} + e^{MIMOt}_{C}, \quad where$$

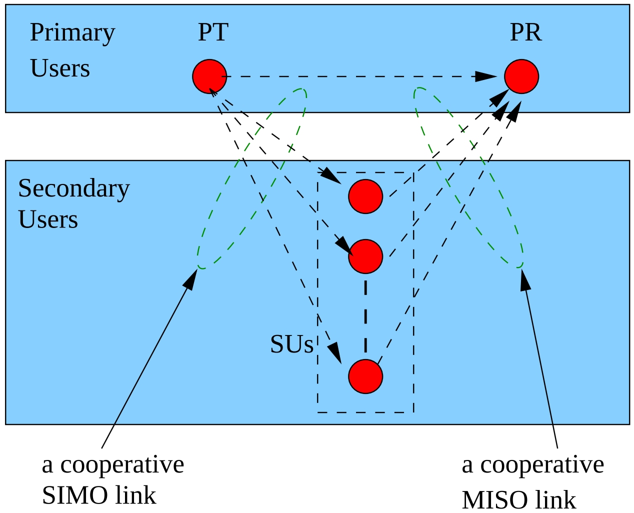


Figure 2: Cooperative MIMO paradigm for overlay systems

$$\begin{aligned} e_{PA}^{MIMOt} &= \frac{1}{mt}(1+\alpha)\overline{e}_b(p,b,mt,mr)\cdot\frac{(4\pi D)^2}{G_tG_r\lambda^2}M_lN_f, \quad and \\ e_C^{MIMOt} &= (P_{ct}+P_{syn})/(bB) \end{aligned} \tag{3}$$

4. Energy consumption per bit at each elementary node for data reception in long-haul $mt \times mr$ cooperative MIMO link

$$e^{MIMOr} = (P_{cr}+P_{syn})/(bB) \tag{4}$$

In the formulas, $P_{ct} = 48.64mw$, $P_{cr} = 62.5mw$, $P_{syn} = 50mw$, $G_d = G_1 d^\kappa M_l$ ($G_1 = 10mw$, $\kappa = 3.5$, $M_l = 40dB$), $\alpha = \frac{3(\sqrt{2^b}-1)}{0.35(\sqrt{2^b}+1)}$, $N_f = 10dB$, $T_{tr} = 5\mu s$, $\sigma^2 = -174dBm/Hz$, $G_tG_r = 5dBi$, $\lambda = 0.1199$. They are the system constants. $\overline{e}_b(p,b,mt,mr)$ is defined by the target BER, constellation size b, and the numbers of cooperative nodes mt and mr at transmission side and reception side, respectively. It can be calculated by numerical analysis according to the following relation [12]

$$p = \varepsilon_H\left\{\frac{4}{b}\left(1-\frac{1}{2^{b/2}}\right)Q\left(\sqrt{\frac{3b}{M-1}\gamma_b}\right)\right\} \tag{5}$$

for $b \geq 2$ and

$$p = \varepsilon_H\{Q(\sqrt{2\gamma_b})\} \tag{6}$$

for $b = 1$. In the formula (5) and (6), $\gamma_b = \frac{||H||_F^2\cdot\overline{e}_b(p,b,mt,mr)}{N_0\cdot mt}$, where $N_0 = -171dBm/Hz$ and $M = 2^b$. H is the matrix of channel coefficients assumed known (it can be estimated by sensing the transmission signals). ε_H denotes the average with respect to H.

3 Cooperative MIMO Paradigm for Overlay System

In an overlay system, the SUs use their power to assist the primary transmission. As in turn, they can use the PUs' frequency resources when the transmission completed. SUs facilitate the PUs based on the knowledge of the PUs' message and/or codebook at the cognitive transmissions. We propose to use m SUs to cooperatively relay the PUs' transmission as shown in Figure 2. We expect that by using cooperative relay the SUs can assist the PUs even when they are far away from the PUs.

Algorithm 1 (Cooperatively relay data for PUs by SUs)
Preprocessing Calculate the value of $\overline{e}_b(p, b, mt, mr)$ for a set of p, b, mt, and mr. Load the table of $\overline{e}_b(p, b, mt, mr)$ in each SU node.

In the following steps, according to p, mt and mr, SU nodes use the table of $\overline{e}_b$ to determine constellation size b which minimizes $\overline{e}_b$.

Step 1 (Data transmission from the primary transmitter to m SUs via a $1 \times m$ SIMO link) The primary transmitter transmits the source data. At the same time, the mt SUs receive the source data using the $1 \times m$ coding system.
At this step, the energy used for each SU node is $E_{Sr} = e^{MIMOr}$, and the energy per bit used for the primary transmitter is $E_{Pt} = e^{MIMOt}(1, m)$.

Step 2 (Data transmission from m SUs to the primary receiver via a $m \times 1$ MISO link) Each SU node transmits the source data to the primary receiver simultaneously using $m \times 1$ coding system.
At this step, the energy per bit used for each SU node is $E_{St} = e^{MIMOt}(m, 1)$, and the energy per bit used for the primary receiver is $E_{Pr} = e^{MIMOr}$.

Based on the energy model presented in previous Section, the energy per bit that each SU node uses for relaying the primary transmitter's data to the primary receiver in the above algorithm is $E_S = E_{St} + E_{Sr} = e^{MIMOt}(m, 1) + e^{MIMOr}$. Assuming that the energy per bit used in data transmission for PUs and SUs are the same, the largest distance between a relay SU from P_t and P_r can be calculated as follows:

1. Let D_1 be the distance between P_t and P_r. Calculate E_1, the energy per bit required for the data transmission from P_t to P_r using the formula E_1=$e^{MIMOt}(1, 1)$.
2. Let $E_{Pt} = E_1$. Calculate D_2, the distance between P_t and the m cooperative SUs (i.e., the length of SIMO link from P_t to the SUs) using the formula E_1=$e^{MIMOt}(1, m)$.
3. Let $E_S = E_1$. Calculate D_3, the distance between the m SUs to P_r (i.e., the length of MISO link from m cooperative SUs to P_r) by using E_S= $e^{MIMOt}(m, 1)$ + e^{MIMOr}.

4 Cooperative MIMO Paradigm for Underlay Systems

In an underlay system, SUs share frequency resources with PUs without any knowledge about the PUs' signals. Since PUs are licensed users, they usually should do nothing when they use their frequencies for communication. SUs are unlicensed users. They try to use PUs frequency without disturb PUs. Therefore the cooperative technology for underlay system is only considered for SUs in this paper. When a source secondary node sends data to a destination secondary node, the data are usually relayed by a route of multiple hops in the CoMIMONet. At each hop, the data are transmitted cooperatively. The SU nodes in the transmission cluster and those in the receiving cluster cooperate on data transmission and reception as shown in Figure 3. In the underlay system, the constraint that the energy of the SUs' transmitted signals falls below the noise floor at the primary receiver in the shared frequency must be satisfied. In order to evaluate the level of the noise, we consider the energy consumed for power amplifiers in the transmission process and omit the energy consumed for the circuits. We focus on the peak value that the energy consumed for power amplifiers in the transmission process.

Algorithm 2 (Cooperative data transmission between SUs)
Preprocessing Calculate the value of $\overline{e}_b(p, b, mt, mr)$ for a set of p, b, mt, and mr. Load the table of $\overline{e}_b(p, b, mt, mr)$ in each SU node.
In the following steps, according to p, mt and mr, SU nodes use the table of $\overline{e}_b$ to determine constellation size b which minimizes $\overline{e}_b$.

Step 1 (Intra/Local transmission at transmit cluster ST): The head x of ST broadcasts the source data to all the other local nodes in ST using different time slots.

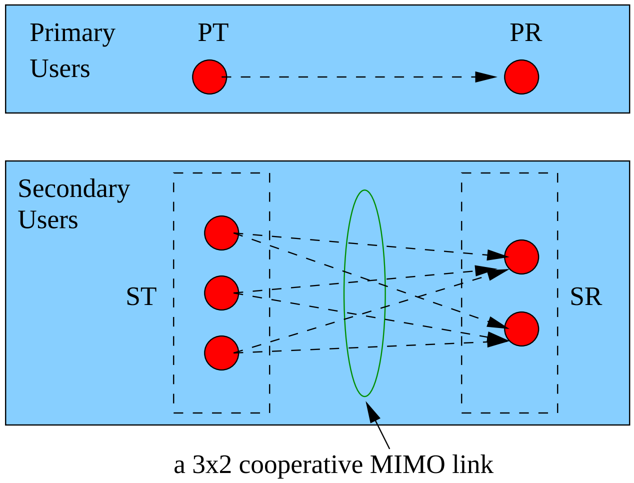


Figure 3: Cooperative MIMO paradigm for underlay systems

The energy consumption per bit used for x in the transmission is the energy per bit used for the primary transmitter is e^{Lt}=e^{Lt}_{PA}+e^{Lt}_{C}. Therefore, the consumed energy for power amplifiers at x is e^{Lt}_{PA}

Step 2 (Transmission between ST and SR with a $mt \times mr$ cooperative MIMO link): Each node i in ST acts as the i-th antenna and encodes the source data using the MIMO code system. All mt nodes in ST broadcast the encoded sequence to the nodes in SR simultaneously.
In the transmission, the energy per bit consumed by each node in ST is $e^{MIMOt}(mt, mr)$. Since mt nodes in ST transmit the data at the same time, the total energy for the power amplifiers is $mt \times e^{MIMOt}_{PA}$.

Step 3 (Intra/Local transmission at SR): Each node in SR transmits the received data using different time slots to the head y of SR. y decodes the received data based on the MIMO code system.
The energy consumption per bit consumed for each node in SR in the transmission is energy e^{Lt}. Since the nodes transmit the data in turn, the energy consumed for power amplifiers at any moment is e^{Lt}_{PA}.

As the result, at any moment during the transmission process, the energy consumption per bit for each node in the transmission will not exceed $E_{PA} = \max(e^{Lt}_{PA}, mt \times e^{MIMOt}_{PA})$.

5 Cooperative MIMO Paradigm for Interweave Systems

Cooperative MIMO can greatly benefit from multiple antennas to limit or avoid interference towards the primary users. In Figure 4, two primary users Pt and Pr and two clusters of secondary users C-St and C-Sr share the same spectrum and space, where Pt transmits the data to Pr and C-St transmits the data to C-Sr simultaneously. To avoid the interference that C-St brings to Pr, the antennas of SU nodes in C-St cooperatively obtain the optimal beamforming pattern that puts the null constraint along the direction to Pr, thus enabling the share of frequency and time resources with no additional interference. In the following algorithm, mt nodes in cluster C-St cooperatively transmit data to mr nodes in cluster C-Sr. In order to put the null constraints to the primary receptor which share the same frequency with C-St, mt nodes of C-St form $\lfloor mt/2 \rfloor$ pairs where $\lfloor x \rfloor$ stands for the nearest integer less than or equal to x. One node of each pair is imposed a phase delay such that the signal wave of two nodes in each pair will be canceled with each other along the

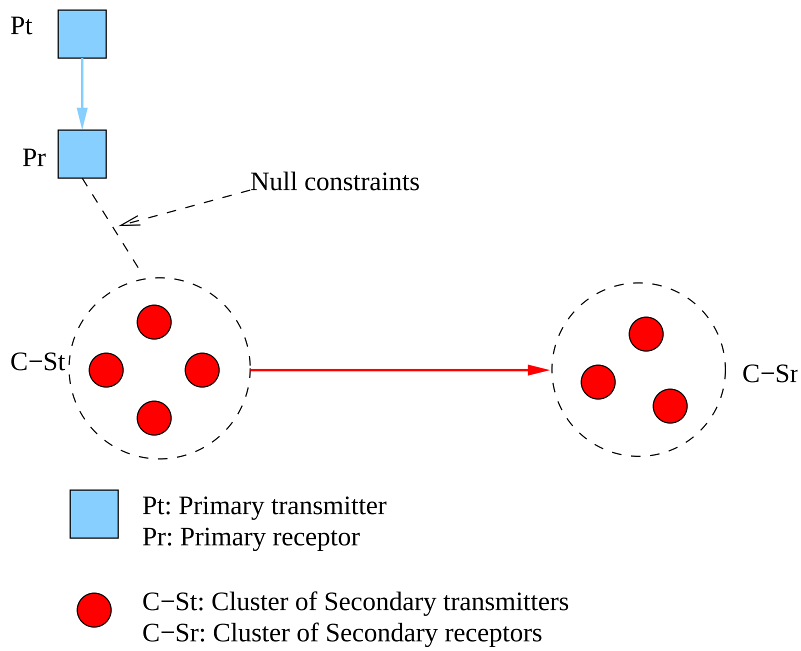


Figure 4: Cooperative MIMO paradigm for interweave systems

direction to the primary receptor. All pairs in C-St take the same action and cluster C-St transmits the data to cluster C-Sr following the steps in Algorithm 2 with a $\lfloor mt/2 \rfloor \times mr$ MIMO link.

Algorithm 3 (Cooperative data transmission between SUs with null constraint)

Step 1 The head of transmission cluster C-St determines the PU to share the frequency based on the sensed environment (In order to minimize the interference, the head can pick the PU such that it is as far as possible from C-St and/or the line segments of C-StPr and C-StC-Sr are not as collinear as possible).

Step 2 Assume that C-St picks the frequency from primary transmitter Pt. $\lfloor mt/2 \rfloor$ pairs of the nodes in C-St and mr nodes in C-Sr form a $\lfloor mt/2 \rfloor \times mr$ MIMO and perform the data transmission following the steps in Algorithm 2. In the transmission process as shown in Figure 5, for each pair of the nodes, say St1 and St2, in C-St, St1 is imposed a phase delay $\delta{=}\pi\left(\frac{2r\cos\alpha}{w}-1\right)$, where r is the distance between St1 and St2, w is the wave length, and α is the angle $\angle PrSt1St2$.

The phase delay $\delta{=}\pi\left(\frac{2r\cos\alpha}{w}-1\right)$ reflects the condition that the signals transmitted from St1 and St2 are canceled with each other along the direction to Pr. With this condition, in Figure 5 the signal wave transmitted from St1 should have a phase delay π when it arrives at point A, where $\angle PrASt2 = \angle PrSt2A$. The formula is accurate when the distance between St1 and Pr is much larger than the distance between St1 and St2. For example, $\delta = \pi$ when $r = w$ and $\alpha = 0$. It is easy to see that two signal waves transmitted from St1 and St2 are canceled with each other at Pr in this case. Now we consider the signal wave that Sr receives. The signals transmitted from $St1$ has a phase delay at point B equal to $\Delta{=}\delta + \frac{2\pi r\sin\beta}{w}$, where $\angle SrBSt2{=}\angle SrSt2B$ and $\beta = \angle St1St2B$. The signal wave towards the direction to Sr is the addition of two signal waves transmitted from St1 and St2. Its amplitude is $\gamma^2 = \gamma_1^2 + \gamma_2^2 + 2\gamma_1\gamma_2\cos\Delta$, where γ_1 and γ_2 are the amplitude of signal waves from St1 and St2, respectively.

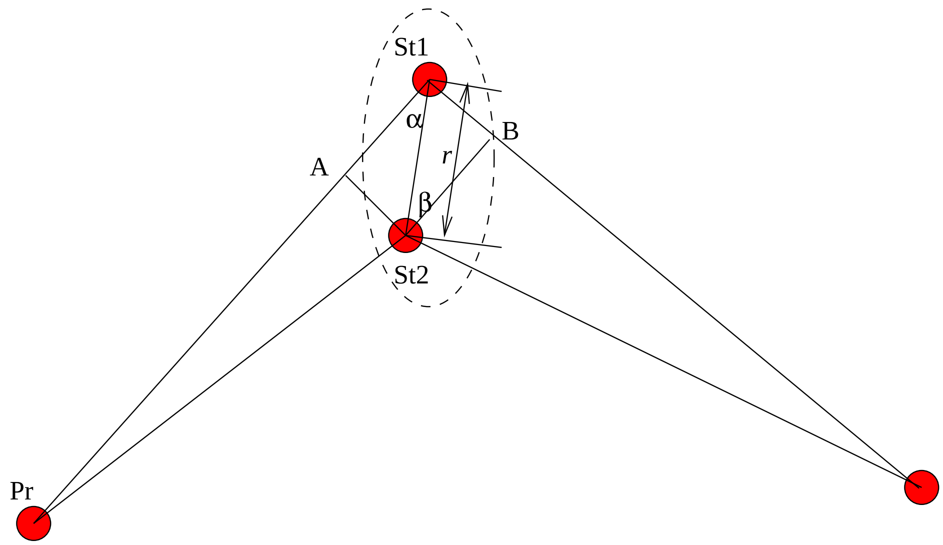


Figure 5: Cooperative MIMO paradigm for interweave systems

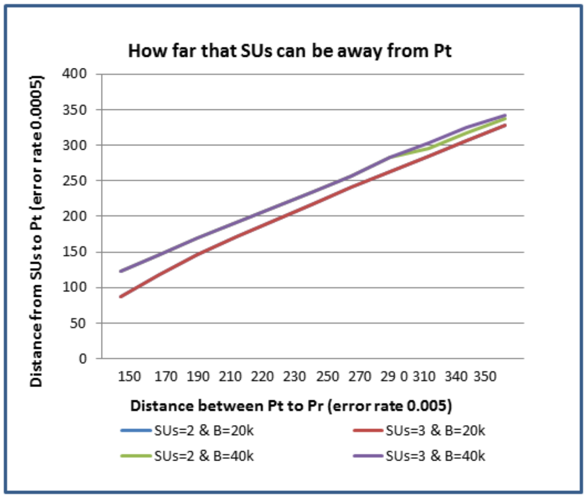
6 Analysis and Experiments

In this section the cooperative MIMO paradigms are evaluated for overlay, underlay and interweave systems in cognitive radio networks through computer simulations and real-world experiments. The experiments are carried out in a cooperative testbed based on GNU Radio [13] and Universal Software Radio Peripheral (USRP) [14]. In computer simulations, the bandwidth B varies from 10k to 100k, and the numbers of cooperative SU nodes in the transmission and receiving sides vary from 1 to 4.

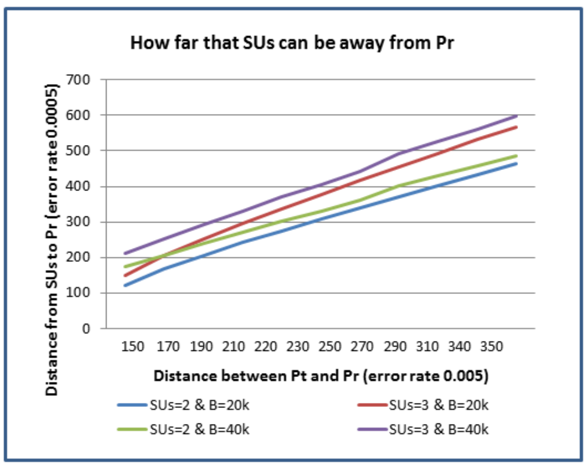
6.1 Analysis of the overlay system

We evaluate the largest distance that the SUs can stay away from the primary transmitter Pt and from the primary receiver Pr, respectively, when the SUs assist data transmission for Pt and Pr. We assume that in the numerical analysis (1) Pr cannot receive the data from Pt if the BER P_b is higher than the given threshold, (2) PUs and SUs use the same amount of energy for data transmission, and (3) when SU nodes cooperatively relay the data from Pt to Pr, Pr receives the data if and only if the error rate lower than the threshold. In the simulations, the distance between Pt and Pr varies from 150 m to 350 m, the minimum value of E_S is found by changing constellation size b from 1 to 16. By setting E_{Pt} to be the same as E_S, the largest distance from SU nodes to the primary transmitter Pt is found from the formula for E_{Pt}, and the largest distance from the SU nodes to the Pr is found from the formula for E_S.

Figure 6(a) shows the largest distance that SUs can be away from Pt. Figure 6(b) show the largest distance that SUs can be away from Pr. In the two figures, the distance between Pt and Pr is shown on x axis with bit error rate set to 0.005, the largest distance between the SUs and Pt/Pr are shown on y axis with bit error rate set to 0.0005 (10 times improved), where PUs and SUs are using the same amount of energy. For example, when Pt transmits the data to Pr in distance 250 meter with bit error rate 0.005, using the same energy the SUs can relay the data to Pr with bit error rate 0.0005 in distance 406 meters away to Pr and in the distance 235 meter to Pt when $m = 3$ and bandwidth = 40k. Therefore, using the proposed overlay scheme, the SUs can relay data for PUs with much lower bit error rate and staying far away from the primary transmitter and from primary receiver. In Figure 6(a), for the cases that their bandwidth is the same the results are almost overlapped. Comparing Figure 6 (a) and (b), we can find that the distance from SUs to Pr is larger than from SUs to Pt. This is because in the overlay system the SUs receive a data stream from the Pt using the SIMO scheme and then transmit it to Pr using the MISO scheme. Transmission needs more energy than reception (see formula (3) and (4) in Section 2.3). Moreover, it



a) Distance that the cooperative SUs can stay away from the primary transmitter



b) Distance that the cooperative SUs can stay away from the primary receiver

Figure 6: Distance that SUs can be away from primary transmitter Pt and primary receiver Pr

is easy to understand that the wider the bandwidth, the shorter the transmission period is required for sending the same amount of data. Therefore, when the number of SUs, error rate and the total energy consumption are specified, wider bandwidth implies that larger tranmission power could be used in this shorter transmission period, which results in longer transmission distance as shown in Figure 6 (a) and (b). Furthermore, the impact of the number of SUs is decided by multiple parameters. If only considering the transmission power, m SUs can make the signal stream m times stronger because they combine m same signal streams when the SUs relay the signal stream from Pt and then transmit the data stream to Pr using the MIMO technique. However, in practice the energy consumed by the circuits should also be considered. Therefore, when error rate, bandwidth and total energy consumption are given the larger number of SUs does not necessary imply larger distances. In Figure 6 (b), under the same bandwidth (B=20k or 40k) the distance that three SUs can relay is larger than two SUs can relay when the distance is larger than 170 meters. However, in Figure 6 (a), under the same bandwidth, the distance that three SUs can relay is almost the same as that two SUs can relay.

6.2 Analysis of the underlay system

In underlay systems, due to strict constraint that the energy of their transmitted signals falls below the noise floor at the primary receiver in the shared frequency, we only consider the energy per bit for the power amplifiers (i.e., e_{PA}, including e_{PA}^{Lt} and e_{PA}^{MIMOt}) used by all SUs during the transmission process. Let d be the largest distance between the SU nodes in transmission side. The formula for e_{PA}^{Lt} in Section 2.3 shows that the larger d is, the larger e_{PA}^{Lt} will be. In the numerical analysis, the distance D between Pt and Pr varies from 100 m to 300 m, mt and mr varies from 1 to 4, d varies from 1 m to 16 m, constellation size b varies from 1 to 16, and BER p_b varies from 0.1 to 0.0005. The results show that the total energy per bit for the power amplifiers of all SUs nodes falls below the noise floor at the PUs for all cases.

Figure 7 shows the total energy per bit for the power amplifiers of all SUs nodes when $d = 1$ m and $p_b = 0.001$. In the upper plot of Figure 7, the case of $mt = 1$ and $mr = 1$ represents the no-cooperative SISO system. It is considered as the model for primary users. We can see that the no-cooperative SISO system requires much more energy than cooperative MIMO systems. The analysis shows that the difference of magnitude is 2 to 4 orders (between 100 to 10000 times). This difference is caused by the constellation size b and the value of $\overline{e}_b(p, b, mt, mr)$. The value of $\overline{e}_b$ can have difference in magnitude up to three orders. For example, when $b = 2$, $\overline{e}_b = 1.90 \times 10^{-18}$ if $mt = mr = 1$ (SISO system) and $\overline{e}_b = 3.20 \times 10^{-20}$ if $mt = 2$ and $mr = 3$ (MIMO system). According to the formula in Section 2.3, e_{PA}^{Lt} is proportional to b and e_{PA}^{MIMOt} is proportional to $\overline{e}_b$. In underlay system, E_{PA} is minimized by choosing the optimal b when mt, mr, D, d, p_b are given.

Since the results for cooperative MIMO systems are almost all overlapped in the upper plot of Figure 7, they are plotted in the lower plot of Figure 7 to compares the total energy per bit for different cooperative MIMO systems so that the difference between the almost overlapped lines in the upper plot of Figure 7 could be clearly displayed. The lines of $mt = 1$ and $mr = 2$, $mt = 1$ and $mr = 3$ and $mt = 2$ and $mr = 3$ are overlapped. They are almost overlapped with the horizontal axis. In these three cases, the number of cooperative transmitters is smaller than that of cooperative receivers; therefore, less amount of total energy is needed. The main reason is that transmission needs more energy than reception, especially when the transmission distance is large. For example, when $mt = 2$ and $mr = 1$, the only receiver receives two data streams from two transmitters. On the other side, when $mt = 1$ and $mr = 2$, each receiver receives one data stream from the only transmitter, and then two receivers will locally share (transmit) its data with each other. Therefore, in both case, two data streams will be received, but the case $mt = 2$ and $mr = 1$ consumes more energy because in this case two transmitters transmit the data in long distance. According to the communication theory, in all six cases, the total energy per bit for the power amplifiers of all SUs nodes falls below the noise floor at the PUs (comparing with the case of $mt = 1$ and $mr = 1$). Using the same method, the total energy per bit for power amplifiers of all SUs nodes when $d = 1$ m to $d = 16$ m is also determined through simulations. The results demonstrate very similar conclusion and are not presented in this paper. We find that the value of d doesn't give any big impact to the energy consumption.

6.3 Analysis of the interweave system

Assume that Pt and Pr are the primary transmitter and primary receiver and C-St and C-Sr are the clusters of secondary transmitters and receivers sharing the same frequency. In order to put the null constraints to Pr, the nodes of C-St form pairs and one node of each pair is imposed a phase delay such that the signal wave of two nodes in each pair will be canceled with each other along the direction to Pr. Since each pair takes the same action, we evaluate the performance for only one pair. Suppose that the pair St1 and St2 in C-St transmit the data to the nodes in C-Sr.

Theoretically, the amplitude of the addition of signal waves from St1 and St2 is zero at Pr. Therefore, there is no interference to Pr (the experiment result in real wireless environment will be shown later). Now we evaluate the amplitude of the addition of signal waves transmitted from St1 and St2 in C-St and received at a node Sr in C-Sr by simulating Algorithm 3. In the simulation, the distance between St1 and St2 is 15m, $r = 1/2\omega$, St1 and St2 are located on the vertical axis such that the horizontal axis passes through the middle of the line segment connecting St1 and St2, and 20 Prs

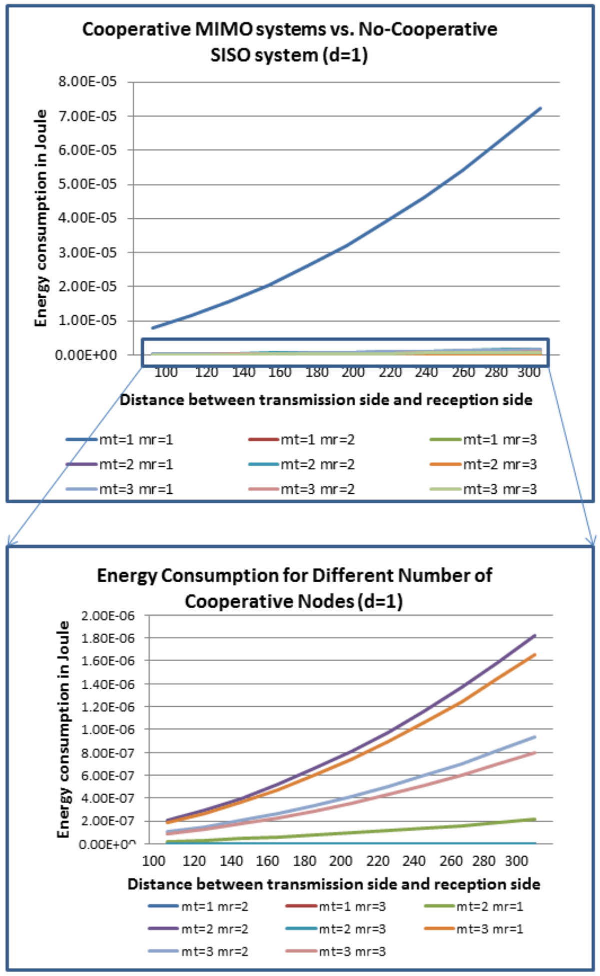


Figure 7: Energy per bit for the power amplifiers in underlay systems when cooperative nodes are in range of 1 meter. Upper plot: Comparing the energy consumption for the cooperative MIMO systems ($mt > 1$ or $mr > 1$) and no-cooperative SISO system ($mt = mr = 1$). Lower plot: Comparing the energy consumption for different number of cooperative SUs at the transmission side and reception side.

are randomly located in a circle centered at St1 with a diameter 300m. According to the algorithm, St1 and St2 pick the Pr such that the resulting line segments of St1 and Pr, St2 and Pr and line segment of St1 and St2 are not as collinear as possible. The simulation repeats 10 times and average amplitude of the signal wave that Sr received is evaluated. Simulation results are listed in Table 1. The simulation shows that the average amplitude of the signal wave that Sr receives is 1.87 times as strong as that of SISO system (data transmission between one single antenna transmitter and one single antenna receiver). It indicates that the proposed paradigm not only avoids the interference but also achieves high diversity gain. The signal strength that Sr receives depends on the angle between line segments StSr and StPr. Specifically, when StSr and StPr are perpendicular to each other, Sr receives a full diversity gain; when they are collinear, Sr receives no signal wave. The reason for achieving high diversity gain is that in Algorithm 3 the PU is picked in such a way that the PU is as far as possible from St and the line segments of StSr and StPr are not as collinear as possible.

Table 1: Amplitude of signal waves from two cooperative SUs in Interweave System

Test Number	Location of Picked Pr	Amplitude
1	(0, -71)	1.87
2	(6, 121)	1.87
3	(-25, -149)	1.88
4	(6, 142)	1.87
5	(12, 145)	1.87
6	(20, 140)	1.87
7	(11, -76)	1.88
8	(41, 116)	1.89
9	(14, 126)	1.87
10	(-7, -143)	1.87

6.4 Performance evaluation in real wireless environment

In order to answer the question that how much performance enhancement cooperative communication can bring in real wireless environment, we build cooperative systems based on USRP platform and GNU Radio. Various cooperative schemes have been evaluated through experiments conducted in in-door environment. For overlay system with single-relay cooperation, the testbed consists of three nodes: one PU transmitter node, one SU relay node, and one PU receiver node. For overlay system with multi-relay cooperation, the testbed consists of five nodes: one PU transmitter node, three SU relay nodes, and one PU receiver node. For underlay system, the testbed consists of two SU transmitter nodes and one SU receiver node. For interweave system, the testbed also consists of two SU transmitter nodes to form cooperative transmit beamformer and one SU receiver node to observe the received signal strength. Each node consists an USRP motherboard and RFX2400 daughterboard as the RF-frontend and a signal processing module implemented in GNU Radio running in a general purpose computer under Ubuntu operating system. The RFX2400 daughterboard works on 2.45GHZ. In order to demonstrate the performance enhancement of the cooperative schemes in different applications, randomly generated binary data are transmitted in the overlay and interweave systems, and image files are transmitted in the underlay systems. The BER performance is used for overlay systems evaluation, the packet error rate (PER) is used for underlay system evaluation, and the received signal strength at different direction (corresponding to the secondary transmitters) is used for interweave system evaluation. The Binary Phase Shift Keying (BPSK) modulation and demodulation are used for overlay and interweave systems. The Gaussian-filtered Minimum Shift Keying (GMSK) modulation and demodulation are used for underlay systems. The bit rates in the transmissions are all set to 250 kbps. The packet size for underlay system is 1500 bytes. The cooperative MIMO paradigms proposed in Section 3, 4 and 5 are used to implement overlay, underlay and interweave cooperations. The equal gain combination is used for overlay systems.

In performance evaluation for overlay system with single-relay cooperation, the transmitter, relay and receiver are located in the corners of an equilateral triangle. The distance between every two nodes is about 2 meters. A thick board is put between the transmitter and receiver to function as an obstacle to reduce the link quality. 100000 binary digits are transmitted. Table 2 shows BER results obtained from three experiments. The BER results are calculated at the receiver. The average BERs were also calculated and shown in Table 2. The results from other experiments are very similar and are available upon request. It is clear that the BER for direct transmission without cooperative relay is rather high due to the obstacle between the sender and the receiver. However, the BER results for system with relay cooperation is much lower, showing that the cooperative MIMO communication can significantly improve the quality of the cognitive communication.

When there are more than one relay nodes to help the transmission between transmitter and receiver, it is expected that the BER performance should be even better. In performance evaluation for overlay system with multi-relay cooperation, the transmitter and receiver are separated in two labs with distance more than 30 feet and multiple concrete walls. Three relays are uniformly put in the corridor between the transmitter and receiver. 100000 binary digits are transmitted. Table 3

Table 2: BER results for single-relay overlay system

Trial	with cooperation	without cooperation
1	2.21%	9.13%
2	2.27%	12.73%
3	2.89%	10.76%
Average	2.46%	10.87%

shows the average BER result obtained from three experiments. The results from other experiments are very similar and are available upon request. The BER results are calculated at the receiver. In Table 3, the relay is located in the middle between the transmitter and receiver for the single-relay case. The experiment results verified that the more relays, the lower bit errors. This experiment also verified that multi-relay nodes can be located further away than single-relay nodes if assuming the same error rate.

Table 3: BER results for multi-relay overlay system

Multi-relay	Single-relay	without cooperation
2.93 %	10.57%	22.74%

For underlay system, the transmit amplitudes of the secondary transmitters are adjusted to achieve different transmission powers to avoid the interference to the primary users. The two secondary transmitters are next to each other and the distance between them and the secondary receiver is about 12 feet. A image file with 474 packets is transmitted simultaneously by the two secondary transmitters for the cooperative case. Table 4 shows PER results obtained from three experiments. The PER results are calculated at the secondary receiver. The results for non-cooperative case are obtained by letting only one secondary transmitter transmit the image file. The average PERs were also calculated and shown in Table 4. The results from other experiments are very similar and are available upon request. It is clear that when there is no cooperation, the PER is very high and the received image cannot be recovered. On the other hand, the PER is very low even when the transmission amplitude is 600. The image could still be recovered and displayed with some distortions. This verified that with cooperative MIMO communication, the secondary users can share the spectrum with the primary users without introduce significant interference.

Table 4: PER results for underlay system

Amplitude	with cooperation	without cooperation
800	0	24.85%
600	6.12%	70.28%
400	13.72%	97.1%
Average	6.61%	64.08%

In the experiment for interweave system, the receiver is located on a semi-circle centered on the midpoint of the two transmit nodes St1 and St2 with diameter of 2 meters. The beamformer is designed to put a null in the direction of 120 degree to two transmit nodes. The received signal amplitude is recorded when the receiver is moved between 0 degree and 180 degree with 20 degree increment. Figure 8 shows the simulated radiation pattern of the designed beamformer, the normalized received signal amplitude with beamformer and the normalized received signal amplitude for SISO system where no MIMO technique is used. It shows that the received signal amplitude is very small in the direction of 120 degree. Since the line of sight propagation is designed in Section 5 and the multipath propagation happens in the in-door experiment environment, the received signal amplitude in the null direction is not zero. Figure 8 also shows that when the receiver is located in the region out of 20 degree from the null direction, the received signal amplitude (the blue dotted line in Figure 8) is larger with beamformer than that (the green dashed line in Figure 8) in SISO

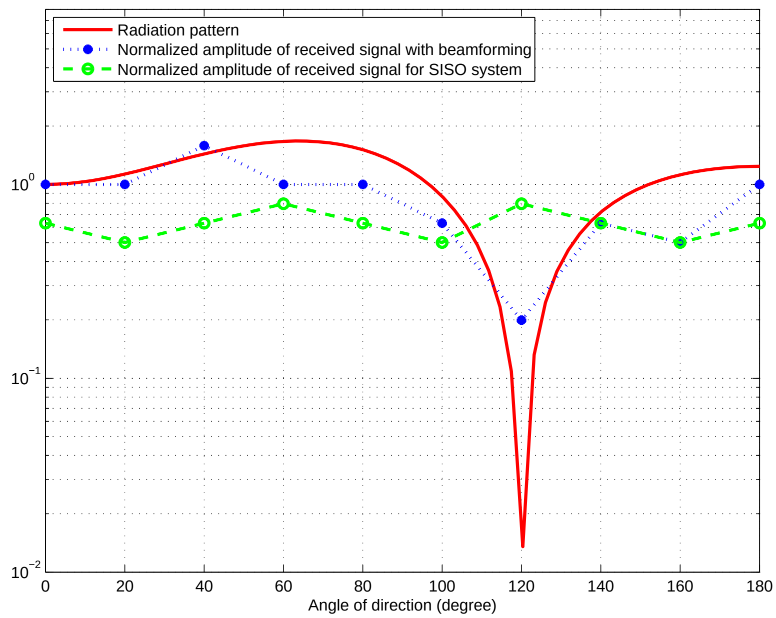


Figure 8: Performance of the cooperative beamformer for interweave system.

system. This verified that with cooperative MIMO technique, the secondary users can pairwisely form a cooperative beamformer to communicate without introducing significant interference to the primary user while still achieve large diversity gain to increase the signal strength to the secondary receiver.

7 Conclusions

This paper proposes efficient cooperative MIMO paradigms for cognitive radio networks. The paradigms can maximize the diversity gain and significantly improve the performance of overlay, underlay and interweave systems. In overlay systems multiple SUs cooperative relay primary transmission even when they are far away from the PUs. In underlay systems the SUs form virtual MIMO networks to share the PUs' frequency resources without any knowledge about the PUs' signals and maintain the strict interference constraint that the spectral density of the SUs' transmitted signals falls below the noise floor at the primary receivers, even when secondary users are close to the primary receivers. In interweave systems, secondary users can use cooperative beamforming to remove the interference to the primary users while still achieving high diversity gain for improved system performance. The advantages and limits of the proposed paradigms are also showed by numerical analysis and real-world experiments.

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