Cooperative MIMO Paradigms for Cognitive Radio Networks

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Abstract—This paper investigates the benefits that cooperation brings to cognitive radio networks. We focus on the cooperative Multiple Input Multiple Output (MIMO) technology, where multiple distributed secondary users cooperate on data transmission and reception. Energy efficient cooperative MIMO paradigms are proposed to maximize the diversity gain and significantly improve the performance of both overlay and underlay systems. In the proposed overlay system the secondary users can assist (relay) the primary transmissions even when they are far away from the primary users. In the proposed underlay system 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. Numerical and experimental results are provided in order to discuss the advantages and limits of the proposed paradigms.

I. 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 this paper we consider underlay and overlay systems of cognitive radios.

In 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 [2], [5]. On the other hand, in 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. In the literatures, the SUs in the underlay systems make decisions in their own interest by maximizing their utility function, while influenced by the other players’ decisions [3], [4]. 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 [5].

Cooperation is a key technology for tackling the challenges of a practical implementation of cognitive radio networks. In [8], cooperative transmission/relaying of primary traffic by SUs is investigated, where a secondary transmitter relays the 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 secondary receiver. In this scheme, the relay happens to be in the convenient location, typically halfway between source and destination.

Multiple Input Multiple Output (MIMO) radio systems employ multiple transmission and reception antennas which can provide extremely high spectral efficiencies by simultaneously transmitting multiple data streams in the same channel. The gains induced by MIMO technology can be used in wireless networks for improving system performance, e.g. raising data rate, reducing error rate, extending communication range. In [1] a game theoretical approach is investigated for MIMO cognitive radios. 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 [10], [7]. 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. We propose energy efficient cooperative MIMO paradigms that can maximize the diversity gain and significantly improve the performance of both overlay and underlay systems. In overlay system we show that the secondary users can relay the primary transmissions even when they are far away from the primary users. In underlay systems we show that the secondary users are allowed to share the primary users’ frequency resources without any knowledge about the primary users’ signals while meet the strict constraint that the spectral density of the secondary users’ transmitted signals falls below the noise floor at the primary receivers, even when secondary users are close...
to the primary receivers. Numerical and experimental results are provided in order to discuss the advantages and limits of the proposed paradigms.

The remaining of this paper is organized as follows. Section II introduces the cooperative MIMO network model and communication schemes. Section III and IV elaborate the proposed cooperative overlay and underlay MIMO paradigms for cognitive radio networks. The numerical analysis and experiment results are given in Section V. Finally, Section VI concludes the whole paper.

II. COOPERATIVE MIMO NETWORK MODEL AND COMMUNICATION SCHEMES

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, we use cooperative MIMO techniques on SUs in order to reduce energy, extend transmission range, reduce error rate, etc. The following discusses the cooperative MIMO network model for SUs.

A. 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. We define a cooperative MIMO network (CoMIMONet) 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 $d$ ($d \leq r$). Let $A$ and $B$ be two $d$-clusters. Suppose 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 can be defined between $A$ and $B$, where node $i$ in $A$ uses its antenna as the $i$-th antenna cooperating on the transmission and 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 SISO link, MISO link, 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 primary nodes. In each cluster there is a special primary node called the head node. The head node retains information of other primary nodes such as ID and battery power level, and the other primary nodes retain the information about the head. The head nodes can control and synchronize the cooperative transmission and reception. They form a spanning tree which is used as the routing backbone. 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 can be found in [10].

B. Cooperative Communication Schemes

In CoMIMONet, multiplehop-based routing is used to forward the data from the source node to the final destination node. We discuss the communication schemes for each hop in the data relay. Suppose there are $mt$ cooperative SU nodes in transmission side $A$ and $mr$ cooperative SU nodes in reception side $B$, and the head node $x$ in side $A$ transmits the data to the head node $y$ in side $B$. The cooperative data communication between $x$ to $y$ consists of intra data communication at $A$ and $B$ and inter data communication between $A$ and $B$, as shown in Fig. 1. The communication MIMO, MISO, and SIMO schemes are described as follows, where the MISO and SIMO schemes are special cases of the MIMO scheme.

MIMO scheme (Fig 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 $A$ using different timeslots. After this step, each node in $A$ has the source data.
Step 2 (Transmission between A and B with a \( m_t \times m_r \) 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 \( m_t \) nodes in A broadcast the encoded sequence to the \( m_r \) 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 (Fig 1 (b)) \((mt > 1 \text{ and } mr = 1)\)

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

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

SIMO scheme (Fig 1 (c)) \((mt = 1 \text{ and } mr > 1)\)

Step 1 (Transmission between A and B with a \( 1 \times m_r \) cooperative MIMO link): The only node \( x \) in A broadcasts the source data sequence to the \( m_r \) nodes in B.

Step 2 (Intra/Local transmission at B): Each node in B transmits the received data using different timeslots to \( y \). \( y \) decodes the received data back to the source data.

C. Energy Model

In this paper, the MIMO systems are referred to the ones coded with space-time block codes (such as Alamouti code) and a flat Rayleigh fading channel as those used in [7]. 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 [6], [7]. For local transmission, a \( \kappa \)-th power path loss with AWGN is assumed. Let \( e^{Lt} \) denote the energy cost per bit for local/intra data transmission. It consists two parts: \( e^{Lt}_{PA} \) the energy consumption per bit of the power amplifiers, and \( e^{Lt}_{C} \) is the energy consumption per bit of the circuit. Let \( e^{Lt} \) denote the energy cost per bit for data reception at each receiving node in the transmission side and each node in the reception side in a cooperative link. Let \( e^{MIMO}(mt, mr) \) denote the energy cost per bit at each transmission node for data transmission in long-haul cooperative MIMO link with \( mt \) cooperative nodes in transmission side and \( mr \) cooperative nodes in reception side. It consists two parts: \( e^{PA}_{MIMO} \) is the energy consumption per bit of the power amplifiers, and \( e^{C}_{MIMO} \) is the energy consumption per bit of the circuit. Let \( E^{MIMO} \) denote the energy cost per bit for data reception at each receiving node in cooperative link. In the following formulas, \( p_B, B, d, D, b, \) 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 \( P_{ct}, P_{cr}, P_{syn} \) are the energy consumptions in circuits for transmission, reception and synchronization.

1) Energy consumption per bit for local/intra data transmission

\[
e^{Lt} = e^{Lt}_{PA} + e^{Lt}_{C}, \quad \text{where}
\]

\[
e^{Lt}_{PA} = \frac{4}{3}(1 + \alpha)^{\frac{b^2}{2}} - 1 \ln \left( \frac{4(1 - 2^{-b/2})}{b} \right) \sigma^2 D_{e} N_f \rho^2
\]

\[
e^{Lt}_{C} = P_{ct}/(bB) + P_{syn} T_{tr}/n
\]

2) Energy consumption per bit for local/intra reception

\[
e^{Lr} = P_{cr}/(bB) + P_{syn} T_{tr}/n
\]

3) Energy consumption per bit for data transmission in long-haul cooperative MIMO link

\[
e^{MIMO}(mt, mr) = e^{PA}_{MIMO} + e^{MIMO}_{C}, \quad \text{where}
\]

\[
e^{PA}_{MIMO}(mt, mr) = mt \left( 1 + \alpha \right) \hat{\tau}(p_B, b, mt, mr)
\]

\[
e^{C}_{MIMO} = (P_{ct} + P_{syn})/(bB)
\]

4) Energy consumption per bit for data reception in long-haul cooperative MIMO link

\[
e^{MIMO} = (P_{cr} + P_{syn})/(bB)
\]

where \( P_{ct} = 48.64 mw, P_{cr} = 62.5 mw, P_{syn} = 50 mw, G_d = G_{1}d^6M_1 \) ( \( G_1 = 10 mw, \kappa = 3.5, M_1 = 40 dB) \), \( \alpha = \frac{0.25(\sqrt{2}\pi - 1)}{0.35(\sqrt{2}\pi + 1)} \), \( N_f = 10 dB, T_{tr} = 5 \mu s, \sigma^2 = -17 dBm/HZ, G_1G_2 = 5 dB, \lambda = 0.1199, \) and \( \hat{\tau}(p_B, b, mt, mr) \) is defined by the target BER, constellation size \( b \), and the numbers of cooperative nodes at transmission side and reception side. It can be calculated by numerical analysis according to the following relationship [6]

\[
p_b = \epsilon_H \left( \frac{\sqrt{3b}}{M-1} \right) Q(\sqrt{\frac{3b}{M-1} \gamma_b})
\]

for \( b \geq 2 \) and

\[
p_b = \epsilon_H Q(\sqrt{2\gamma_b})
\]

for \( b = 1 \), where \( \gamma_b = \frac{||H||^2 \hat{\tau}(p_B, b, mt, mr)}{N_0 mt} \) with \( N_0 = -17 dBm/HZ \) and \( M = 2^b \).
III. 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 when the transmission completed. SUs facilitate the PUs based on the knowledge of the PUs’ message and/or codebook at the cognitive transmissions. Instead of using a single SU to relay the transmission from one PU (source) to another PU (destination) which requires the SU locates at the halfway between source PU and destination PU, we propose to use m SUs to cooperatively relay the transmission as shown in Fig 2 so that the SUs can assist the PUs even when they are far away from the PUs. The m SUs cooperatively relay the PUs’ data with the following two steps:

**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 to m SUs using the SIMO coding system. At this step, the energy per bit used for the primary transmitter is \(E_{Pt} = e^{MIMO}(1,m)\), and energy used for each SU node is \(E_{Sr} = e^{MIMO}\).

**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 \(E_{St} = e^{MIMO}(m,1)\), and the energy per bit used for the primary receiver is \(E_{Pr} = e^{MIMO}\).

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 is \(E_s = E_{St} + E_{Sr} = e^{MIMO}(m,1) + e^{MIMO}\).

**Remarks:**

1. \(\tau_b(p_b, m, b, ml, mr)\) can be precalculated by the numerical analysis. Assume that a table is \(\tau_b(p_b, b, ml, mr)\) is given to each SU node, the SU nodes can use this table to determine the optimal constellation size \(b\) that minimizes the energy consumption, \(E_s\).
2. When \(E_{Pt}\) is determined in Step 1, the largest distance, \(D_1\), from the SU nodes to the primary transmitter can be calculated from the formula for \(e^{MIMO}(1,m)\) in Section II C. Also, when \(E_S\) is determined, the largest distance, \(D_2\), from the SU nodes to the primary receiver from the formula for \(e^{MIMO}(m,1)\) and \(e^{MIMO}\).

IV. COOPERATIVE MIMO PARADIGM FOR UNDERLAY SYSTEMS

In an underlay system, SUs share frequency resources with PUs without any knowledge about the PUs’ signals. When a source primary node sends data to a destination primary node, the data are usually relayed by a route of multiple hops in the CoMIMONet. At each hop, the data are relayed by using three steps of the MIMO scheme described in Section II B. The SU nodes in the transmission cluster and those in the receiving cluster cooperate on data transmission and reception as shown in Fig 3. At each hop 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. Since only transmission energy brings interference, we focus on the transmission energy in this study. In other words, we consider the energy for the power amplifiers and omit the energy consumed at the circuits. Therefore, the energy consumption per bit in Intra/Local transmission at either transmission cluster \(A\) or reception cluster \(B\) is \(e^{La}_{PA}\), and the energy consumption per bit for transmission between \(A\) and \(B\) with cooperative MIMO link is the sum of the energy for the power amplifiers at all the nodes in the transmission cluster, i.e., \(ml \times e^{MIMO}_{PA}\). Therefore, at any moment during the transmission process, the energy consumption per bit for power amplifiers at all SUs in an underlay cooperative MIMO system is \(E_{PA} = max(e^{La}_{PA}, ml \times e^{MIMO}_{PA})\).

Assume that a table of \(\tau_b(p_b, m, b, ml, mr)\) is given to each SU node. The SU nodes can use the table to determine the optimal constellation size \(b\) to minimize \(E_{PA}\).

V. NUMERICAL ANALYSIS AND EXPERIMENTS

This section presents the numerical analysis for both overlay and underlay systems through computer simulations and the experiment results carried out in a cooperative testbed based on GNU Radio [12] and Universal Software Radio Peripheral...
A. Numerical Analysis of the Overlay System

In this section, we evaluate the largest distance that the SUs can stay away from the primary transmitter \(Pt\) and primary receiver \(Pr\) 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 first found by changing constellation size \(b\) from 1 to 16. Let \(E_{Pt}\) be the same value as \(E_s\). The largest distance from SU nodes to the primary transmitter \(Pt\) is then found from the formula for \(E_{Pt}\), and the largest distance from the SU nodes to the primary receiver is found from the formula for \(E_s\).

Fig 4(a) shows the largest distance that SUs can be away from \(Pt\). Fig 4(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 SU nodes and PT/\(Pr\) are shown on \(y\) axis with bit error rate set to 0.0005 (10 times improved). Comparing Fig 4(a) and (b), we can find that the distance from SUs to \(Pr\) is larger than from SUs to \(Pt\).

B. Numerical 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 used by all SUs during the transmission process, i.e., \(E_{PA}\). Let \(d\) be the largest distance between the SU nodes in transmission side. The formula for \(E_{PA}\) in Section II shows that the larger \(d\) is, the larger \(E_{PA}\) 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, 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 SU nodes falls below the noise floor at the PUs for all cases.

Fig 5 shows the total energy per bit for the power amplifiers of all SU nodes when \(d = 1\) m and \(P_b = 0.001\). In the upper plot of Fig 5, 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). Since the results for cooperative MIMO systems are almost all overlapped in the upper plot of Fig 5, they are plotted in the lower plot of Fig 5 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 Fig 5 could be clearly displayed. The lines of \(mr = 1\) and \(mt = 2\), \(mr = 1\) and \(mt = 3\), and \(mt = 2\) and \(mr = 3\) are overlap with each other. They are the optimal solutions. According to the communication theory, the total energy per bit for the power amplifiers of all SU 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 SU nodes when \(d = 16\) m is also determined through simulations. Due to the page limitation, the results were not shown here.
results. The average BERs were also calculated. It is clear that the cooperative MIMO communication can significantly improve the quality of the cognitive communication.

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VI. CONCLUSIONS

This paper proposes energy efficient cooperative MIMO paradigms for cognitive radio networks. The paradigms can maximize the diversity gain and significantly improve the performance of both overlay and underlay systems. In overlay systems multiple SUs relay the primary transmissions 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. The advantages and limits of the proposed paradigms are shown by numerical and experimental results.

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