A New Antenna Selection Algorithm in Cognitive MIMO Systems

Zhang Nan, Xu Yemao and Gao Xiao

***Abstract*—Utilization of multiple antenna transmission technique is a potential solution to co-channel interference problems in coexisting environments. However, additional system cost and complexities associated with multiple antennas limit their application in CR Systems. In this paper we introduce antenna selection in cognitive MIMO systems and propose low complexity antenna selection algorithms. Wherein, using only a subset of available antennas to transmit or receive signal greatly reduce hardware cost and complexities of the CR transceivers; while keeping much of the benefits of multiple antennas.**

***Index Terms*—Multiple-Input Multiple-Output (MIMO), Cognitive Radio(CR).**

I. INTRODUCTION

Looming spectrum scarcity and its low utilization motivated the development of innovative spectrum sharing technologies to improve spectrum utilization efficiency. Cognitive radio (CR) is considered as a promising technology that enable secondary network to dynamically utilize the licensed spectrum, under the condition that no harmful interference is caused to the primary operations [1]. However; in such coexisting scenarios where cognitive radios communicate with each other by opportunistically utilizing the spectrum, a secondary (CR) user usually has to tradeoff between two conflicting goals; maximizing its own throughput, and to minimize the interference it produces at each primary user [4]. Multiple antenna techniques, promising diversity and capacity gains may also be an efficient solution to combat interference in such co-existing environments [3]. Multiple antenna can be used to allocate transmit dimensions in space and hence provide the secondary transmitter in CR network more degree of freedom in space in addition to time and frequency, so as to balance between its conflicting goals[4]. Moreover, in OFDM-based CR system by transmitting different data on different antennas, the resource loss due to carrier deactivation in LUs band and bit rate loss due to windowing can be compensated [4]. In [5], it was demonstrated that capacity of MIMO systems increases linearly with min(NT，NR), where NT and NR denote the numbers of transmit and receive antennas respectively. However, the main drawback of multiple antenna techniques is the cost of radio frequency (RF) chains, including low noise power amplifiers, gain control units, digital to analog converters and several filters, which are the major cost of a system. Increasing the number of antennas will lead to significant increase in system size, cost and complexity, since each antennas requires a RF link.

In order to reduce the system/hardware cost as well as to preserve the advantages of MIMO systems, a promising technique referred to as antenna selection is presented in [6]. With this method; the RF chains can be optimally connected to the best subset of the transmitter (or receiver) antennas. It has been demonstrated that the system performance using antenna selection techniques is better than the full-complexity systems with the same number of antennas but without selection [6]. However, the only mechanism for optimum selection of antenna is exhaustive search of all possible combinations for one that gives the best SNR (for diversity) or capacity (for spatial multiplexing). The complexity of optimally selecting the best transmit/receive antenna grows exponentially, which is computationally inefficient. Moreover, CR are likely to face dynamic environments where antenna selection changes with changing channel conditions hence, a computationally efficient antenna selection algorithm is required.

In this paper, we address antenna selection in cognitive MIMO system to reduce its cost while keeping much of the benefits of the multiple antennas. We formulate the antenna selection problem in cognitive MIMO system as a combinatorial optimization problem.

In Such co-existing environment, our main goal is to maximize the capacity of cognitive MIMO system under interference constraints to primary users. However, adding spatial dimension to the CR resource allocation problem increases the size and complexities of an already immense parameter space, for which optimal solution is computationally inefficient. We apply evolutionary techniques for antenna selection problem and their effectiveness is verified through simulations under different scenarios. Simulation results verify that both evolutionary techniques Genetic algorithm (GA) and Binary Particle swarm Optimization (BPSO)-based antenna selection algorithms provide a low complexity solution to the

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problem, which greatly reduce hardware cost and complexities of cognitive MIMO system, while keeping much of the benefits of the multiple antennas. Proposed algorithms achieve near optimal system capacity over wide range of SNR, while abiding by the interference constraints to the primary users.

II. MIMO IN COGNITIVE SYSTEMS

The main problem of the cognitive radios operating in coexisting environment is the co-channel interference. Multiple-antenna transmission technique (MIMO) is a potential solution to this problem. It uses space diversity and can offer multiplexing gain, diversity gain and co-channel interference suppression to the wireless system because of the independent channel fading between different pairs of antennas. Considering downlink transmission in a coexisting environment; where the. Two systems know all the transmitted signals, the dirty paper coding (DPC) is seen as the optimal approach for the sum capacity performance [7, 8]. However, major concerns in CR system are not just the sum capacity, and the particular challenge of the CR is that both the transmitters and receivers are distributed and may be unable to coordinate with each other. The maximum ratio transmission (MRT) method presented in [9] maximizes the received signal-to-noise ratio (SNR), but it does not consider the interference to the other radio system and therefore degrades its performance. The zero-forcing (ZF) method; which comes from multiple input and multiple output multi-user detection (MIMO-MUD) techniques [10], perfectly mitigates the interference to other radio systems. However, it may degrade the power of desired signals and lose some of the diversity gain of the channel. The method proposed in [11] for secret communications in MISO case maximizes the secrecy capacity, which is equal to the difference between message channel capacity and interference channel capacity. In this method the interference power might be small in some cases, but it also might be strong when doing this leads to a great performance increase for the desired user. However, this is not allowed for the CR environment since usually the performance of the primary system should be guaranteed and the interference power should be controlled below a certain value.

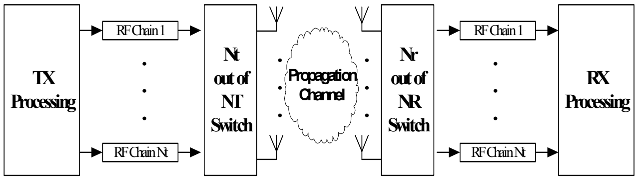

Fig. 1 Block diagram of a MIMO system with transmit and receive antenna selection

Some previous work using multiple-antenna techniques in CR environments has been performed in scenarios where only the transmitter side employs multiple antennas. These linear approaches, including maximal ratio transmission (MRT); zero-forcing (ZF); optimal interference free (IF), and optimal interference-constrained (IC), are based on beamforming technologies; and can avoid or control the CCI, therefore improving the system performance [3]. However, the main drawback of multiple antenna techniques is the cost of radio frequency (RF) chains, including low noise power amplifiers, gain control units, digital to analogue converters; and several filters, which are the major cost of a transmitter. Increasing the number of antennas will lead to a significant increase in the cost since each antenna requires a RF link.

A. *Antenna selection*

In MIMO systems, adding complete Radio Frequency (RF) chains may result in increased complexity, size and cost. These negative effects can be drastically reduced by using antenna selection. This is because antenna elements and digital signal processing are considerably cheaper than introducing complete RF chains. In addition, many of the benefits of MIMO schemes can still be obtained [12, 13]. Besides, perfect CSI is not required at the transmitter as the antenna selection command can be computed at the receiver and reported to the transmitter by means of a low-rate feedback channel.

In Fig. 1, we show a typical MIMO wireless system with antenna selection capabilities at both transmit and the receive sides. The system is equipped with N_T transmit and N_R receive antennas, whereas a lower number of RF chains has been considered ($N_t < N_T$ and $N_r < N_R$ at the transmitter and receiver, respectively). In accordance with the selection criterion, the best sub-set of N_t transmit and N_r , receive antennas are selected. This reduces the number of required RF chains, thus leads to significant savings. In order to convey the antenna selection command to the transmitter, a feedback channel is needed but this can be done with a low-rate feedback as only $\begin{pmatrix} N_r \\ N_t \end{pmatrix}$ bits are required.

Originally, antenna selection algorithms were born with the purpose of improving link reliability by exploiting spatial diversity. More precisely, a reduced complexity system with antenna selection can achieve the same diversity order as the system with all antennas in use. However, as MIMO schemes gained popularity, antenna selection algorithms began to be adopted in spatial multiplexing schemes aimed at increasing the system capacity.

A brief review of the state of the art is presented below, where different methodologies are classified according to the context: spatial diversity or spatial multiplexing.

B. *Antenna Selection for Spatial Diversity*

In a wireless environment, by separating the receive antennas far enough the correlation between the channel fades is low. Then, by selecting the best receive antenna in terms of channel gains, a diversity order equal to the number of receive antennas is obtained. Winters considered a similar procedure in a Multiple-Input Single-Output (MISO) system to exploit diversity at the transmit side with the help of a feedback channel [8]. In that work, the antenna selection algorithm was very simple: when the received SNR was below a specific threshold a command is sent to the transmitter to indicate that the transmit antenna must be switched. For the SIMO case, more sophisticated receive antenna selection algorithms based on Hybrid Selection/maximal-ratio combining techniques were derived in [15]. The basic idea of those algorithms was to select the best (in terms of SNR)LN out of N receive antennas and combine the received signals

By means of a maximal ratio combining (MRC) procedure. By doing so, apart from exploiting the diversity gain, array gain can also be extracted. The extension to MIMO systems were presented by Molisch et. al. [14, 15] in a scenario where antenna selection was only performed at the transmitter in combination with a maximal ratio transmission (MRT) strategy. It was shown that by selecting the best sub-set of transmit antennas; the degradation in system performance is slight in comparison with the saving in terms of hardware cost. The obtained results can be easily generalized to those cases performing antenna selection at the receive side of the MIMO link due to the reciprocity of the SNR maximization problem. An interesting result was obtained0 in [16] for those systems performing MRC at the receiver side and an antenna selection mechanism (with a single active antenna) at the transmitter. It was shown that the achieved-diversity order is equal to NB, with B standing for the position taken by the channel gain of the selected antenna when arranging the channel gains of the different transmitters in an increasing order.

C. *Antenna Selection for Spatial Multiplexing*

In spatially correlated MIMO fading channels, capacity gains can be lower than expected since spatial multiplexing gains mainly come from resolving parallel paths in rich scattering MIMO environments. With this problem in mind, Gore et al. proposed one of the first papers where antenna selection was adopted in a MIMO context. In that paper, the authors showed that system capacity cannot be improved by using a number of transmit antennas greater than the rank of the channel matrix. By considering that, an algorithm (exhaustive search) was proposed where only antennas satisfying the full rank condition were selected. As a result, system capacity gains were obtained with respect to the full antenna system, since transmit power was efficiently distributed.

Upper bounds of the achievable capacity with antenna selection were derived in [14]. In particular, it was shown that capacity results close to those of the full antenna system can be achieved by selecting the best $N_r = N_T$ out of NR receive antennas. In [15], a sub-optimal approach was proposed for both transmit and receive antenna selection. By starting with the full channel matrix, those rows (columns) corresponding to the receivers (transmitters) minimizing the capacity loss are iteratively dropped. As shown in [15,16], almost the same capacity as with an optimal selection scheme can be achieved with an incremental version of the mentioned selection algorithm; i.e., by using a bottom-up selection procedure. In [16] it was also proven that the diversity order achieved with receive antenna selection is the same as that with the full antenna scheme; where the diversity order was defined as the slope of the outage rate. Although a sub-optimal approach with decoupled transmit and receive selection was adopted in [8], similar conclusions in terms of the diversity-multiplexing trade-off curare [9] were drawn. That is, the same trade-off curve, as with all antennas in use can be obtained with transmit and receive antenna selection.

D. *Antenna Selection in Cognitive MIMO Systems*

The antenna selection mechanisms outlined above are for the systems without additional interference constraints as posed by cognitive radios. As discussed earlier, cognitive radios operating in coexisting scenarios have to optimize their performance under their own power as well interference constraints of the primary users. Therefore, problems implementing antenna selection in cognitive MIMO systems need to account for these CR specific constraints. Moreover, the proliferation of multiple antennas in cognitive radio systems increases the size and complexities of an already immense parameter space, for which computationally efficient antenna selection mechanisms are required.

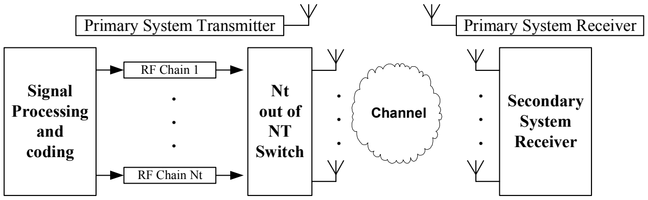

Fig 2 Block diagram of a cognitive MIMO system with transmits and receives antenna selection

Given these opportunities and challenges thus far, only a small set of published literature investigates antenna selection in cognitive systems. To reduce complexity of cognitive broadcast systems having a large number of secondary users (and only one PU), a subset of users and single receive antenna selection was presented in [16]. However, the attempt to reduce the system complexity is compromised by serving a subset of selected users with one receive antenna and at the cost of significant reduction in sum-rate capacity. Hence, true benefits of MIMO like transmit diversity are not utilized. Moreover in practical co-existing environment cognitive systems have to operate in an environment proliferated with a mass of legitimate primary users where, cognitive radios have to limit their transmissions to avoid any harmful interference at the primary users. In coexisting environments more chances of interference are from the transmit side. Wherein, utilizing multiple antennas on the transmit side and performing antenna selection for a subset of useful antennas which create little or no interference to the primary users, can improve overall performance of cognitive systems. But, to the best of our knowledge no published work has so far been cited addressing transmit antenna selection in cognitive MIMO systems.

In this paper we address transmit antenna selection in cognitive MIIVIO system to reduce the system cost. We formulate the transmit antenna selection in cognitive MIMO system, while considering its own power and interference constraints of the primary users. And propose low complexity transmit antenna selection algorithms for cognitive MIMO system that provide near optimal performance over a wide range of signal to noise ratio.

III. SYSTEM MODEL

We consider cognitive mufti-input mufti-output (MIMO) systems with N_T transmit antennas and N_R received antennas as shown in Fig. 2. There are M primary users each equipped with single antenna. Because of cost concern, we consider a system that has only N_t RF chains at the transmitter, where $N_t = N_T$. It is assumed that the receiver and transmitter has the channel side information (CSI). We denote the channel state between cognitive MIMO systems by the complex matrix $H \in C^{N_R \times N_T}$ and the channel state between the cognitive transmit antennas and M primary users by the complex matrix $G \in C^{M \times N_r}$ On the basis of this known CSI, the transmitter selects at most Nt transmit antennas from the N_T transmit antennas for the transmission so that interference to the primary users is under some threshold.

A. Problem formulation

As discussed earlier, the capacity of MIMO system under assumptions of white Gaussian noise assumptions N_0, is given as:

$$C = \log 2 \det(I_{N_r} + \frac{P}{N_0 N_t} HH^H) \quad (1)$$

where, P is the total transmitter power, I_{N_r}, is $N_r \times N_r$ identity matrix and H^H denotes the conjugate transpose of channel matrix H We assume that transmitter allocates power uniformly among the selected transmit antennas and channel inputs to these antennas are uncorrelated. We formulate the transmit antenna selection in cognitive MIMO system as combinatorial optimization problem. Our main goal of antenna selection in cognitive MIMO system is to maximize the capacity of secondary system under interference constraints to primary users. Mathematically:

$$\max \quad \log 2 \quad \det\left(I_{N_r} + \frac{P}{N_0 N_t} H\Omega H^H \right) \quad (2)$$

Subject to the constraints

$$C1: \quad trace(\Omega) \le N_t$$

$$C2: \quad \sum_{i=1}^{N_t} \left(\frac{P}{N_t} \Omega(i,i) \right) G(m,i) \le I_m \quad for\ all\ m = 1,...,M$$

where, Ω is a diagonal indicator matrix, whose diagonal entries are either 1 or 0 depending on whether an antenna is selected or not. Example. Let N_t =2 and N_T =5. The one possible value of Ω can be:

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

B. Transmit antenna selection in cognitive MIMO

The most straight forward method to obtain the optimal transmit antenna subset is exhaustive search. However, the complexity of optimally selecting transmit antenna increase exponentially with the number of transmit antennas. Exhaustive Search

Algorithm (ESA) evaluates all possible $\sum_{i=1}^{N_t} \binom{N_T}{i}$ combinations of transmit antennas to select the antenna combination that gives the best performance (such as channel capacity, bit error probability, etc.). Enumerating over all possible combinations and finding the one that can give best performance is computationally inefficient. Therefore, low complexity algorithms are required to solve antenna selection in cognitive MIMO system. Evolutionary techniques, have successfully been applied for low complexity solution to the CR parameter adaptation and to the other combinatorial optimization problems of communication systems. In this paper, we apply genetic algorithm (GA) and binary particle swarm optimization (BPSO) for transmit antenna selection in cognitive MIMO system. The fitness function used by GA and BPSO-based antenna selection algorithms to converge to optimal solution is objective function (2) under the constraints $C1$ and C2.

IV. SIMULATION RESULTS AND ANALYSIS

Simulations are performed to validate the effectiveness of proposed antenna selection algorithms as well as to compare their performance with optimal exhaustive search algorithm (ESA). In our simulations we receive antennas under the assumptions distributions. Generate channel gains between transmit and that they have independent complex Gaussian distributions.

For performance analysis we present simulation results of eight different scenarios having different number of total/selected transmit antennas, as well as different number of primary users and interference thresholds: For all of these scenarios, the population size of the individuals/particles for GA/BPSO is 20 and the maximum number of generation/iteration is set to 20.GA uses a crossover rate and mutation probability of 0.9 and 0.1 respectively. Whereas, the parameters for BPSO are, $c1 = c2 = 2,\ V_{\max} + 7\ to\ \text{-}7$ Figures 3 to 10, show system capacity as a function of signal to noise ratio (SNR). The effectiveness of the proposed antenna selection algorithms is verified in various co- existing scenarios and over a wide range of SNR.

In figures 3 and 4, with same number of primary users and selected antennas for secondary transmissions, an increase in tolerable interference limit ($I_{\max}$) by the primary users in Fig.4, yields increased CR system capacity at higher SNR. Because of the fact that, CR is able to transmit at higher power while still obeying interference constraints of the primary users. Whereas, an increase in number of primary users in Fig. 5, increases chances of interference and hence decreases CR system capacity compared with Fig. 3, having the same interference thresholds.

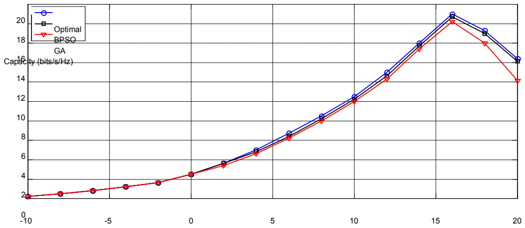

Fig.3 System capacity versus SNR with $N_T = 16$, $N_t = N_R = 5$, $M = 2$ and $I_{\max}$ =1mW

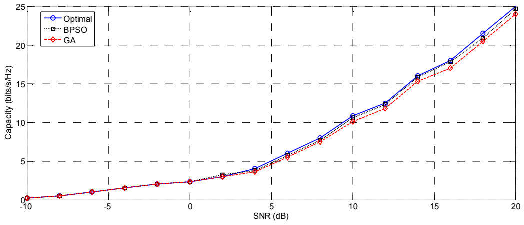

Fig.4 System capacity versus SNR with $N_T = 16$, $N_t = N_R = 5$, $M = 2$ and $I_{\max}$ =10mW

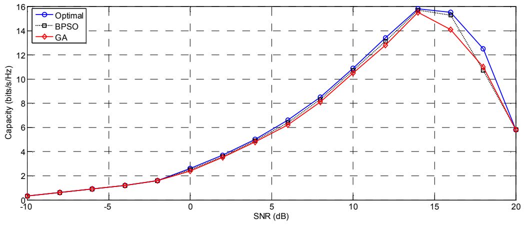

Fig.5 System capacity versus SNR with $N_T = 16$, $N_t = N_R = 5$, $M = 4$ and $I_{\max}$ =1mW

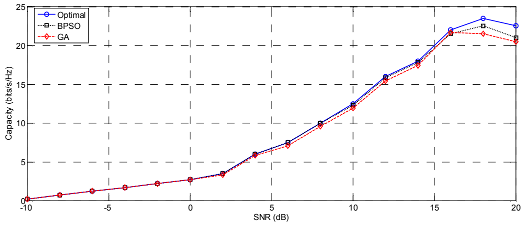

Fig.6 System capacity versus SNR with $N_T = 20$, $N_t = N_R = 6$, $M = 1$ and $I_{\max}$ =1mW

In figures 6 to 8, number of selected transmit antennas and primary users interference threshold are same whereas, number of primary users are varied. The same is the case in figures 9 and 10. In all these scenarios, an increase in number of primary users results in reduction of CR system capacity at higer SNR. Because, with increased number of primary users, interference constraints for secondary (CR) operation increase too. Therefore, CR has to limit its transmit power to avoid unacceptable level of interference to the primary users.

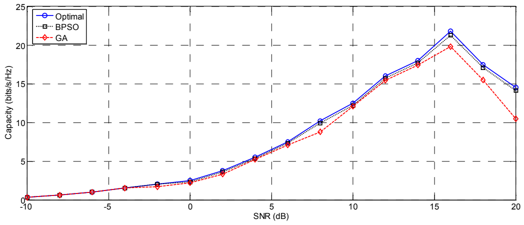

Fig.7 System capacity versus SNR with $N_T = 20$, $N_t = N_R = 6$, $M = 4$ and $I_{\max}$ =1mW

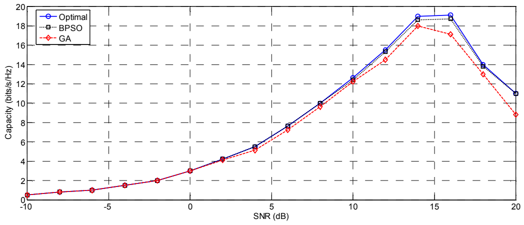

Fig.8 System capacity versus SNR with $N_T = 20$, $N_t = N_R = 6$, $M = 6$ and $I_{\max}$ =1mW

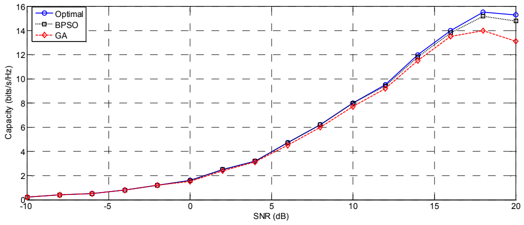

Fig.9 System capacity versus SNR with $N_T = 18$, $N_t = N_R = 4$, $M = 1$ and $I_{\max}$ =1mW

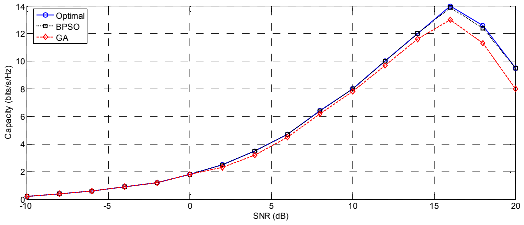

Fig.10 System capacity versus SNR with $N_T = 18$, $N_t = N_R = 4$, $M = 4$ and $I_{\max}$ =1mW

Simulations results verify that, proposed algorithms achieve system capacity near to that of optimal exhaustive search algorithm (ESA). They effectively select and utilize subset of transmit antennas, which greatly reduces system cost and complexities. They maximize capacity of the cognitive MIMO system under interference constraints to primary users, with much lesser computational complexity as compare to optimal ESA.

V. CONCLUSION

In this paper, we outlined state of art on MIMO techniques along with an overview of antenna selection mechanism. We presented transmit antenna selection algorithms based on evolutionary techniques to reduce the cost and complexities of cognitive MIMO systems. Antenna selection was formulated as a combinatorial optimization problem with the main goal to maximize the capacity of cognitive MIMO system under interference constraints to legitimate primary users. The effectiveness of proposed algorithms is verified through simulations in different scenarios and compared with that of optimal exhaustive search algorithm (ESA). Simulation results show that proposed algorithms achieve system capacity near to that of high complexity optimal ESA, over a wide range of SNR, while adhering interference constraints to the primary users. The simple model, low implementation complexity and near optimal performance of evolutionary algorithms-based antenna selection, all make it a suitable solution to reduce hardware cost and complexities of cognitive MIMO systems, while keeping much of the benefits of the multiple antennas.

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