Antenna Selection in MIMO Cognitive Radio

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ABSTRACT

Wireless users use radio frequency (RF) channels for data and message communication. The recent research reviles that the most appropriate to tackle the issues related to spectrum utilization is a function of time and space calls for dynamic access strategies that adapt to the electromagnetic environment. Cognitive radio is one such solution with the ability to sense the RF channel evaluation and adaptively react intelligently in order to optimize the usage of the available spectrum. In this paper we focus on opportunistic resource allocation between the access points (AP) and the wireless stations (STA) for the required spectrum management policies of the wireless systems. A concurrent communication of the cognitive users, competing over the physical resources for the end users. Based on the requirements of this we propose and analyze a channel capacity [6] enhancement technique to design a cognitive multiple input multiple output (MIMO) transceiver system and propose low complexity antenna selection [15] algorithms. Using this technique only a subset of the available antennas to transmit or receive signal greatly reduce the cost and complexity of the physical layer resources of cognitive MIMO system.

Keywords

Spatial diversity, MIMO, RF Chain, Spatial multiplexing, Cognitive Radio, Binary Particle Swarm Optimization.

1. INTRODUCTION

The legacy wireless communication systems uses single input single output (SISO) technology to send and receive signals. MIMO [13][14] provides multiple data streams within a single frequency channel. Each data stream within the channel has its own antenna pair for transmitting and receiving its RF chain and its own analog to digital converter. When a signal is created it is sent to all receiving antennas and all receivers listen for any transmitting signals. Using this method has two or more transmitted signals can be fused together to improve the quality of reception. This intern improves the QoS. As the numbers of antennas are increased more data can be collected, which interns improve the performance [1] of the wireless channel.

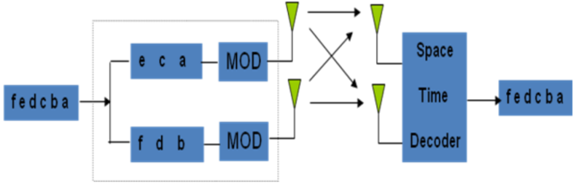

Fig. 1. Data encoding in MIMO system

Wireless connection using MIMO systems enables increased spectral efficiency and link reliability for a given total transmitted power. Increased capacity [2] is achieved by introducing additional spatial channels, which are exploited using space-time coding [5]. The spatial diversity improves the link reliability by reducing the adverse effects of link fading and shadowing.

The channel capacity [6] in theory is defined as the achievable information transfer rate per unit bandwidth that can be transmitted with low probability of error. This is generally expressed in bps/Hz. SISO uses a single channel transmission the maximum channel capacity is defined by Shannon's equation; $C_{SISO} = \log_2[1+SNR]$. It shows that the channel capacity [6] can be increased only with wider transmission bandwidth. A wireless channel has a limited bandwidth over single channel transmission practically there is no chance of fulfilling the above said requirements.

MIMO [13][14] is the heart of IEEE 802.11n standard. It is an extension of the earlier 802.11a/b/g standards, which is added with the multiple antennas in the physical layer of WLAN. The advantages of using IEEE 802.11n with multiple antennas at the transmitter/receivers are; all the antennas both at transmitting and receiving end are used simultaneously to transmit and receive the signals. The multiple receivers in the receiving side not only increases the amount of receiver power but also reduces multipath problems by combining the received signals for each frequency components separately. This improves the performance [1] and also enhances the QoS. To enable this both transmitters and receivers must have multiple RF processing chains to go with their multiple antennas as shown in the fig.2.

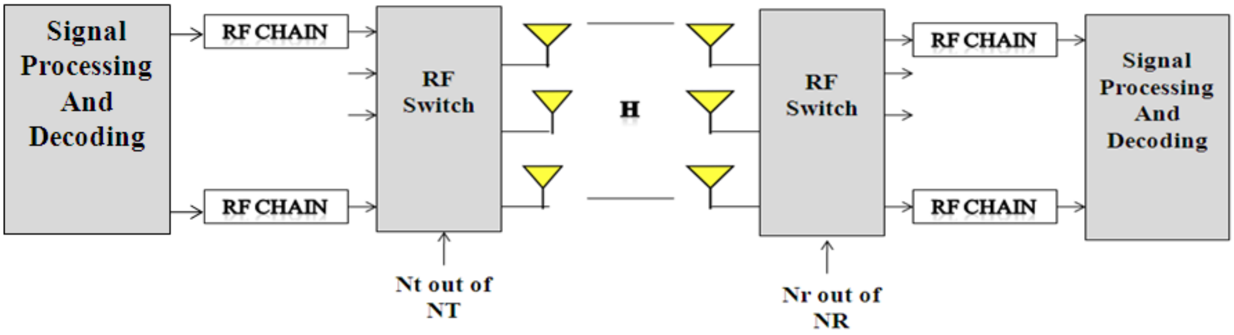

Fig.2. MIMO system with transmit and receive antenna selection with RF chain

MIMO [13][14] uses two basic classes of multiple antenna techniques, the spatial diversity technique and spatial multiplexing [7] techniques. Spatial diversity technique increases the reliability and range by sending or receiving redundant streams of information in parallel along the different spatial paths between transmitters and receiver antenna. Whereas the spatial multiplexing increases the performances [1] by sending independent streams of information in parallel along the different spatial paths between transmit and receive antennas. This improves the performance because if we take care in how we construct and decode signals adding an antenna and independent streams of information need not slow down the stream that are already being sent.

The capacities [2] of a MIMO system increases linearly with $\min(N_{T,}N_R)$, where N_T and N_R denote the number of transmit and receive antennas respectively. However the main limitation of the MIMO [13][14] system is the cost of the RF chains. Increasing the number of antennas will lead to significant increase in system size, cost and complexity. To reduce the cost of the RF chain the subset of the transmit and receive antennas are to be optimally selecting the best transceiver grows exponentially, which is computationally inefficient. Moreover cognitive radio [12] are likely to face dynamic environments where antenna selection [15] 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 [17] to reduce its cost while keeping much of the advantages of MIMO system. By using this technique our objective is to maximize the capacity of Cognitive MIMO system [17] under interference constraints of primary user. We apply evolution technique for antenna selection problem and their effectiveness is verified through Binary Particle Swarm Optimization (BPSO) technique. This method achieve near optimal system capacity over wide range of SNR, and minimizing the CCI to the primary users.

Rest of this paper is organized as follows: In section II we first give an overview of the spatial diversity and section III explore the MIMO system and MIMO system capacity. We then detail our solution and analysis using BPSO algorithm in section IV. The last section concludes on the issues and presents future work.

2. SPATIAL DIVERSITY:

Spatial diversity is one of the techniques used to fight against the deep fading [16]. The diversity technique improves the performance [1] in the presence of fading channel [16]. In this technique signals are transmitted and received through a number of channels instead of one channel. The main idea behind the diversity is that when several copies of the same signals are passed through different channels then they experience independent fading of each other. There will be high probability that some signals will undergo deep fading which other may not. When these signals reach the receiver then there will be significant energy to make a decision that what was actually sent. In MIMO, spatial diversity can be achieved by using the number of antennas both at the transmitter and receiving ends. These antennas are used to pick up the signals from the RF chain at the transmitting end and transmit the same using different channels. At the receiving end the numbers of antennas are used to pick up the transmitted signals coming from different multipath fads.

The main idea of diversity technique is to compare and combine different copies of the received signals coming from independent fading channels [16] to increase the received power at the receiver as in fig. 2 the different diversity combining techniques are;

1. Selection combining- select the best SNR in the antenna branch
2. Equal gain combining – almost the same in MRC in performance
3. Maximum ratio combining – select the best SNR

A traditional wireless channel is modeled by the equation

$$y = x + n$$

Where x is the channel input and n is the fading [16] or channel noise. Consider an environment in which there is no line of sight (NLOS) between the transmitter and the receiver. For this kind of environment 'n' is modeled as zero mean, complexes Gaussian random variable with variance 0.5 per dimension. In case if the fading n is fixed deterministic number rather than a random variable, the channel SNR would be given by,

$$SNR(h)=\frac{E|hx|^2}{E|n^2|}$$

$$=SNR|h|^2$$

2.1 Transmit diversity

In a wireless system with more than one transmitting and only one receiving antenna as shown in the fig. 3, this system is called as a multiple input single output (MISO) system.

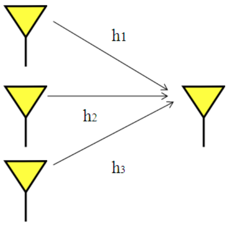

Fig. 3. Transmit diversity

Let N_T be the number of transmitting antennas. The received signal in the receive side is given by

$$y=\sum_{j=1}^{N_T}h_jx_j+n \qquad (1)$$

Where h_j is the fading corresponding to transmit antenna $j\ and\ x_j$ is the symbols sent through antenna j. fading changes from channel to channel. Suppose that we transmit $xw_j,\quad j=1\ 2\ 3........n \quad (2)$

Where w_j's are some weighting factors satisfying

$$\sum_{j=1}^{N_T}|w_j|^2=1 \qquad (3)$$

The above constraint ensures we are not increasing the transmission power.

Substituting (2) in (1) we get $y=x\sum_{j=1}^{N_T}h_jw_j+n$ The SNR of the above channel is given by

$$SNR_{(h_1\,.....h_M}=\frac{E\left|x\sum_{j=1}^{N_T}h_jw_j\right|}{E|n^2|}$$

$$=SNR\left|\sum_{j=1}^{N_T}h_jw_j\right|^2$$

If we could like to maximize the SNR, then set the value

$$w_j=\frac{h^*{}_j}{\sqrt{\sum_{j=1}^{N_T}|h_j|^2}}$$

The SNR is maximized to the value

$$SNR_{(h_1\,.....h_M}=SNR\sum_{j=1}^{N_T}|h_j|^2$$

With respect to the MRC we obtain

$$P_r\{\in\}\le\frac{1}{\left[1+\frac{SNR}{2}\right]^{N_T}}$$

2.2 Receive diversity

Consider the SIMO channel depicted in the fig. below.

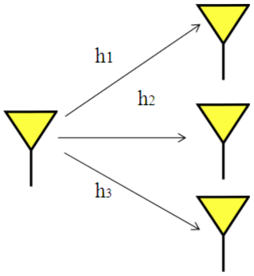

Fig. 4. Receive diversity

Let N_R be the number of receive antennas. The signal received in antenna i is given by

$$y_i=h_ix+n_i \qquad i=1\ 2\ 3...........N$$

Where h_i *and* n_i the fading and noise respectively by i^{th} antenna are sufficiently spaced from each other. Consider the weighted combination of the antennas inputs

$$y = x\sum_{j=1}^{N_R}\alpha_j y_j$$

$$= x\sum_{j=1}^{N_R}\alpha_j h_j + \sum_{i=1}^{N_R}\alpha_i n_i$$

Where α_i 's are some deterministic numbers. The SNR of the above channel is given by

$$SNR_{(h_1 \ldots\ldots h_N} = \frac{E\left|x\sum_{j=1}^{N_R}\alpha_j h_i\right|^2}{E\left|\sum_{i=1}^{N_R}\alpha_i n_i\right|^2}$$

$$= SNR\frac{\left|\sum_{i=1}^{N_R}\alpha_i h_i\right|^2}{\sum_{i=1}^{N_R}\left|\alpha_i\right|^2}$$

The error probability obtained by the maximum likelihood receiver when applied to the MRC output satisfies.

$$P_r\{\in \left|h_i \ldots\ldots h_N\right.\} \le \exp\left\{-\frac{SNR(h_1 \ldots\ldots h_N)}{2}\right\}$$

$$= \left\{-\frac{SNR\sum_{i=1}^{N_R}\left|h_i\right|^2}{2}\right\}$$

Let $z_i = \left|h_i\right| \qquad i = 1\ 2\ 3 \ldots\ldots\ldots N$

$$P_r\{\in \left|z_1 \ldots\ldots z_N\right.\} \le \exp\left\{-\frac{SNR\sum_{i=1}^{N_R} z_i^{\,2}}{2}\right\} \qquad (4)$$

Zi’s are statistically independent, Rayleigh distributed random variables. Thus their joint density is simply given by the product of their individual densities.

$$f(z_1 \ldots\ldots\ldots z_N) = \prod_{i=1}^{N} 2\,z_i \exp\{-z_i^2\} \qquad (5)$$

Averaging (4) with respect to (5) yields

$$P_r\{\in\} \le \int_0^\infty \exp\left\{-\frac{SNR\sum_{i=1}^{N_R} z_i^{\,2}}{2}\right\} \times \prod_{i=1}^{N_R} 2\,z_i \exp\{-z_i^2\}dz_i \ldots\ldots\ldots dz_N$$

$$= \frac{1}{\left[1+\frac{SNR}{2}\right]^{N_R}}$$

From the expression it is clear that by using N_R receive antennas we have managed to substantially reduce error probability.

2.3 Spatial multiplexing and capacity

Spatial multiplexing [7] takes advantages of the extra degree of freedom provided by the independent spatial paths to send independent streams of information at the same time over the same frequencies. When the wireless channel has sufficient degree of freedom the data streams transmitted from multiple transmit antennas can be separated thus leading to parallel data paths. At the receiver these streams are combined and decoded. By using the antennas to divide the transmit power over these degree of freedom, the transmitter can divide its power to send N spatial streams of data, each getting an SNR of f when considered at the receiver.

The capacity of the radio channel under these conditions grows with $\min(N_T\ N_R)$ that is linearly with the number of antennas.

3. MIMO SYSTEMS

Consider the MIMO [13][14]systems with multiple antennas at both the ends. N_T Transmit and N_R receive antennas. The received signal at antenna i is given by

$$y_i = \sum_{j=1}^{N_T} h_{ij} x_j + n_{i,} \quad i = 1,2,3,\ldots\ldots N$$

The channel matrix H is a $N_T \times N_R$ complex valued matrix.

h_{ij} is the fading corresponding to the path from transmit antenna j to received antenna i .

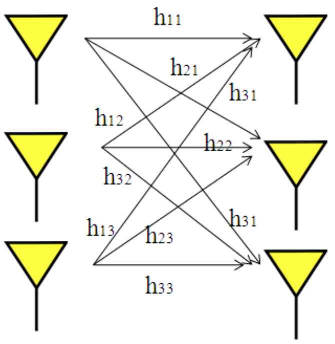

Fig. 5 MIMO system model

Let us consider that the fading is independent n_i is the nose corresponding to receive antenna i

$$\underline{y} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{bmatrix}, \quad \underline{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_M \end{bmatrix}, \quad \underline{n} = \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_N \end{bmatrix},$$

$$H = \begin{bmatrix} h_{11} & h_{12} \cdots h_{1M} \\ h_{21} & h_{22} \cdots h_{2M} \\ \vdots & \vdots \quad \cdots \quad \vdots \\ h_{N1} & h_{N2} \cdots h_{NM} \end{bmatrix}.$$

Then $y = Hx = n$

3.1 MIMO system capacity

In this section we derive the capacity [2][4] of wireless MIMO channel and its comparison with SISO. The error probability of a MIMO network with N_T transmit and N_R receive antenna is,

$$P_r\{\in|H\} \le \exp\left\{-\frac{SNR\|H\|^2}{2_{\min}\{N_R, N_T\}}\right\}$$

Rearranging

$$P_r\{\in\} \le \frac{1}{\left[1+\frac{SNR}{2_{\min}\{N_R, N_T\}}\right]^{MN}}$$

Thus transmit or receive beam forming we have a diversity order $N_T N_R$, referred to as full diversity. The antenna gain on the other hand satisfies,

$$\max\{N_R, N_T\} \le \mathit{antenn\ \ gain} \le N_T N_R$$

The capacity of the wireless SISO channel is given by,

$$C_{SISO} \log_2\left[1+\frac{E|x|^2}{E|n|^2}\right]$$

$$=\log_2\left[1+\frac{P}{2\sigma^2}\right]$$ Where P is the transmission power $P = E|x|^2$ Form the above expression for SISO channel it is clear that the capacity cab be increased only if the transmission power is increased.

For a MIMO wireless channel the capacity [2][4] is calculated as

$$C_{MIMO} = \log_2 \det\left[I + \frac{P}{2\sigma^2}\frac{1}{N_T}Q\right] \quad (6)$$

Where $P = \sum_{j=1}^{N_T} E|x_j|^2$ Is the total transmission power radiating from the transmit antennas. In (6) averaging the expression with respect to the Rayleigh distribution of the fading yields

$$C_{MIMO} = \min\{N_T, N_R\}\log_2\left[I + \frac{P}{2\sigma^2}\right]$$

The multiplexing gain is defined as

Multiplexing gain $=\dfrac{C_{MIMO}}{C_{SISO}}$ under the same transmission power P the multiplexing gain $=\min\{N_T, N_R\}$

Hence using multiple antennas both at transmitter and receiver we can increase the throughput.

The spatial diversity concept of MIMO is one of the best solution to minimize the co-channel interference (CCI) with spatial diversity it can offer multiplexing gain, diversity gain and CCI. The main problem of the cognitive radio (CR) [12] operating in co-existing environment is that both transmitter and receivers are distributed and may be unable to coordinate with each other. The maximum ratio transmission (MRT) method present in maximize the received SNR, but it does not consider the interference to the other radio system and therefore changed its performance [1]. However these techniques are not allowed for CR because the performance of the primary system should be guaranteed and the interference power should be controlled below a certain value. The usual technique like Maximum ratio transmission (MRT), Zero forcing (ZF), optimal interference free (IF) and interference constrained (IC) are based on beam-forming technologies and can minimize or control the CCI, therefore improving the system performance. However the main problem in MIMO system is the cost of RF chains and digital to analog converter. Increasing the number of physical antenna will lead to a signified increase in the cost of the entire system.

3.2 Antenna selection

In a MIMO system the increased complexity size and cost of the RF chain can be drastically reduced by suitably selecting the number of transmitting and receiving antennas. MIMO in fig.2 has N_T transmit and N_R receive antennas. Where N_t and N_r are the RF chain $(N_t < N_T \text{ and } N_r < N_R)$. According to the appropriate antenna selection [15] criterion, the best sub-set of N_t transmit and N_r receive antenna are selected. This reduces the number of RF chain, thus leads to significant savings. In order to convey the antenna selection information to the transmitter, a feedback channel is needed.

3.3 Antenna selection in Cognitive MIMO system

There are antenna selection algorithms for spatial diversity and spatial multiplexing [7]. Whereas the cognitive radio operating in coexisting scenarios have to optimize their performance under their own power as well interference constraints of the primary users. The antenna selection process for cognitive MIMO system [17] needs to account for the CR specific constraints. The transmit antenna selection method in cognitive MIMO system is to reduce total system cost while considering its own power and interference constraints of the primary users. This helps to device the transmit antenna selection algorithms for cognitive MIMO to provide optimal performance over a wide range of SNR

4. COGNITIVE MIMO SYSTEM MODEL

Consider a cognitive MIMO system [17] with N_T transmits antennas and N_R receives antennas. There is M number of primary users each connected to a single antenna. These N_T antennas are connected N_t RF chains at the transmitter; $N_T = N_t$ .Assuming that the receive and transmitter has the channel state information (CSI), we denote the channel state between cognitive MIMO system by the matrix. $\boldsymbol{H} \in \boldsymbol{C}^{N_R \times N_T}$ And the channel between cognitive transmit antennas and M primary users by the complex matrix $\boldsymbol{G} \in \boldsymbol{C}^{M \times N_r}$ .Based on this CSI the transmitter selects at most N_t transmit antennas from the N_T transmit antennas for the transmission, so that interference to the primary user is under some threshold. The capacity of MIMO system under the assumption of white Gaussian noise No is given as

$$C_{MIMO} = \log_2 \det\left[I + \frac{P}{2\sigma^2}\frac{1}{N_T} Q \right]$$

Where

$Q = HH^H \ \text{if} \ N_R < N_T$, Where P is the total transmitter power, I_{N_r} *is* $N_r \times N_t$ identity matrix.

We assume that the transmitter allocates power uniformly among the selected transmit antennas and channel input to these antennas are un-correlated. We formulate the transmit antenna selection in cognitive MIMO system [17] as combinational optimization problem. The main object of antenna selection and cognitive MIMO system is to maximize the capacity of secondary systems under interference constraints to primary users.

$$= \max\ \log_2 \det\left[I + \frac{P}{2\sigma^2}\frac{1}{N_T} H\Omega H^H \right]$$

Subject to the constraints.

Constraint 1: trace $\Omega \le N_t$

Constraint2:

$$\sum_{i=1}^{N_t}[\frac{P}{N_t}\Omega(i,i)]G(m,i)\le I_m \; for \;\; all \; m=1,......M$$

Where Ω is a diagonal indicator matrix whose diagonal entries are either 1 or 0 depending on whether an antenna is selected or not. The complexity of optimally selecting transmit antenna increase exponentially with the number of transmit antennas. In this paper we apply the low complexity algorithm like binary particle swarm optimization (BPSO) for transmits antenna selection in cognitive radio.

4.1 Simulation and analysis

The performance of antenna selection for cognitive MIMO system is performed by simulation. For performance analysis we present simulation result of four different scenarios having the combinations of different numbers of selected transmit antennas as well as different number of primary users and interference threshold. The analysis report is shown in the fig. 6 to 12 with system capacity as a function of SNR. With the same number of primary users and the selected antennas for secondary transmissions an increase in tolerable interference limit by the primary users. Fig. 7 yields increased CR system capacity at higher SNR.

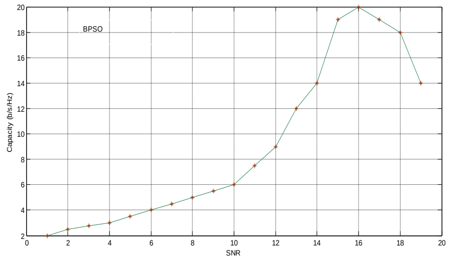

Fig.6. SNR versus system capacity with $N_T = 16$, $N_t = N_R = 5,\ M = 2$

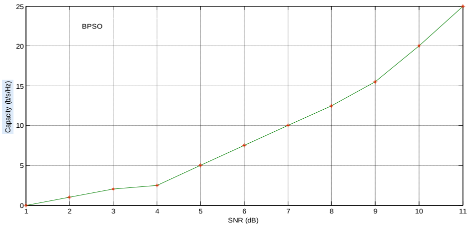

Fig.7. SNR versus system capacity with $N_T = 16$, $N_t = N_R = 5,\ M = 1$

This is due to the fact that CR is able to transmit at higher power while still obeying interference constraints of the primary users. In the fig.8 as the number of primary users are increased there is a chance of increased interference and hence the CR system capacity comparing the fig.6 having the same interference threshold.

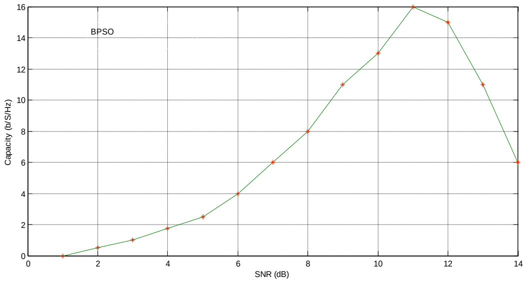

Fig.8. SNR versus system capacity with $N_T = 16$, $N_t = N_R = 5,\ M = 4$

In fig.9 the number of selected transmit and receive antennas and primary users interference threshold are same, whereas number of primary users are reduced. In all these cases an increase in the number of primary users results in reduction of CR system capacity at higher SNR.

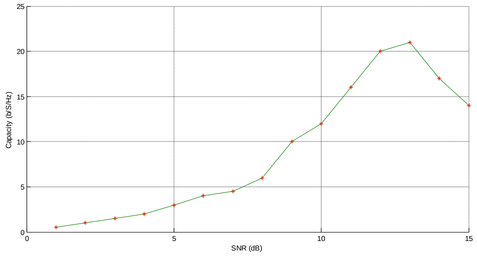

Fig9. SNR versus system capacity with $N_T = 20$, $N_t = N_R = 6,\ M = 4$

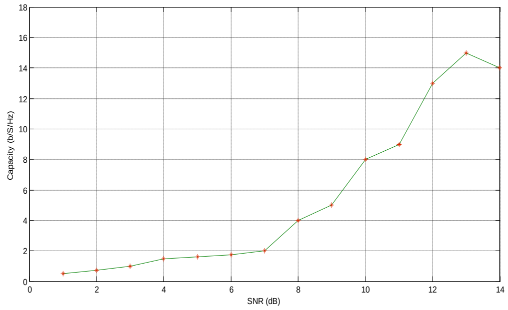

Fig.10. SNR versus system capacity with $N_T = 18$, $N_t = N_R = 4$, $M = 1$

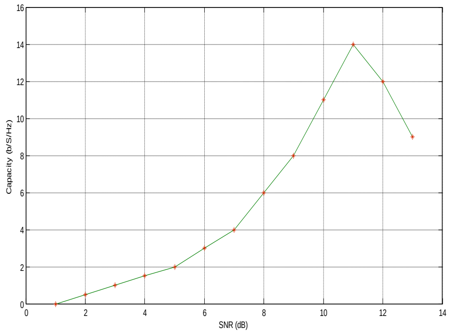

Fig.11. SNR versus system capacity with $N_T = 18$, $N_t = N_R = 4$, $M = 4$

This is due to the increased number of primary users, interference constraints for secondary (CR) option increases too. Therefore CR has to limit it’s transmit power to avoid unacceptable level of inference to the primary users.

5. CONCLUSION

In this paper we derived the capacity and performance of MIMO system. Comparison between MIMO and SISO shows that there is an enhancement in the performance compared to SISO. In the antenna selection process we presented transmit antenna selection algorithm based technique to reduce the complexity and cost of RF chain of cognitive MIMO system. The effectiveness of the proposed binary particle swarm optimization (BPSO) algorithm is verified through simulation in different scenarios and variables. The simulation result shows that proposed algorithm achieves system capacity with a wide range of SNR. This work should be extended in a direction that would adapt the Genetic Algorithm.

6. REFERENCES

[1]. E.Baccarelli, M.Biagi, C.Pelizzoni, N.Cordeschi, F.Garzia, ”Interference Suppression in MIMO systems for Throughput Enhancement and Error Reduction”, IWCMC, 3-6 July 2006, Vancouver, pp.611-616, July 2006.

[2]. D.W. Bliss, K.W. Forsythe, and A.F. Yegulalp, “MIMO Communication Capacity Using Infinite Dimension Random Matrix Eigenvalue Distributions,” *Thirty-Fifth Asilomar Conf. on Signals, Systems & Computers* 2, *Pacific Grove, Calif., 4–7 Nov. 2001*, pp. 969–974.

[3]. D.W. Bliss, K.W. Forsythe, A.O. Hero, and A.F. Yegulalp, “Environmental Issues for MIMO Capacity,” *IEEE Trans. Signal Process.* 50 (9), 2002, pp. 2128–2142.

[4]. R. S. Blum, “MIMO Capacity with Interference,” *IEEE Journal on Selected Areas in Communications*, vol. 21, no. 5, pp. 793–801, 2003. [12] J. Ma, Y. J. Zhang, X. Su, and Y. Yao, “On Capacity of Wireless Ad Hoc Networks with MIMO MMSE Receivers,” *IEEE Transactions on Wireless Communications*, vol. 7, no. 12, pp. 5493–5503, 2008.

[5]. D. Gesbert, M. Shafi, D. Shiu, P. J. Smith, and A. Naguib, “From Theory to Practice: An Overview of MIMO Space–Time Coded Wireless Systems,” *IEEE Journal on Selected Areas in Communications*,vol. 21, no. 3, pp. 281–302, 2003.

[6]. D. Gesbert, H. Bölcskei, D.A. Gore, and A.J. Paulraj, “Performance Evaluation for Scattering MIMO Channel Models,” *Thirty-Fourth Asilomar Conf. on Signals, Systems & Computer*1, *Pacific Grove, Calif., 29 Oct.–1 Nov. 2001,* pp. 748–752.

[7]. A. Gorokhov, D.A. Gore, and A.J. Paulraj, "Receive antenna selection for mimo spatial multiplexing: Theory and algorithms", IEEE Trans. On Signal Processing-Special Issue on MIMO Wireless Communications, vol. 51, no. 11, pp. 2796-2807, Nov. 2003.

[8]. K. Hamdi, W. Zhang and K. B. Latief, User scheduling in Cognitive MIMO 2008. "Low-Complexity Antenna Selection and Broadcast systems", proc of IEEE ICC.

[9]. S. Haykin, “Cognitive Radio: Brain–Empowered Wireless Communications,” *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 2, pp. 201–220, 2005.

[10]. J. Jiang, et al., “Correlation Analysis of Multiple-Input Multiple-Output Channels with Cross-Polarized Antennas,” Proceedings of APCC2008, 2008.

[11]. N. Jindal, “MIMO Broadcast Channels with Finite-rate Feedback”, *IEEE Trans. Inform. Theory,* vol. 52, no. 11, pp. 5045-5060, Nov 2006.

[12]. S.-J. Kim and G. B. Giannakis, "Optimal Resource Allocation for MIMO Ad Hoc Cognitive Radio Networks," in *Proceedings of the 46th Annual Allerton Conference on Communication, Control, and Computing*, 2008, pp. 39–45.

[13]. A.J.Paulraj, D.A.Gore, R.U.Nabar, H.Bolcskei, "An Overview of MIMO Communications: A Key to Gigabit Wireless", Proc. of IEEE, pp.198- 218, Feb. 2004.

[14]. Peter Cain, "Using Channel Condition Number to Visualize MIMO Performance," IWPC MIMO, 12 November 2008

[15]. Rathnakar Achary, V. Vaityanathan, Pethur Raj Chellaih, S. Nagarajan "Antenna selection for performance enhancement of MIMO Technology in Wireless LAN" IJCSI International Journal of Computer Science Issues, Vol. 8, Issue 1, January 2011

[16]. W. Santipach and M. L. Honig, "Capacity of a Multiple-Antenna Fading Channel with a Quantized Precoding Matrix," IEEE Trans. Inform. Thoery, vol.55, No.3, pp. 1218-1234, Mar. 2009.

[17]. G. Scutari, D.P. Palomar, and S. Barbarossa, "MIMO cognitive radio: A game theoretical approach," submitted to *IEEE Trans. on Signal Processing (2008)*. See also *Proc. of the 9th IEEE Workshop on Signal Processing Advances for Wireless Communications (SPAWC)*, Recife, Pernambuco, Brazil, July 6–9, 2008.

[18]. "Spatial Channel Model for Multiple Input Multiple Output (MIMO) Simulations," 3GPP TR 25.996, V7.0.0, available on line at http://www.3gpp.org/FTP/Specs/html-info/25996.htm.

[19]. R. Tresch, M. Guillaud, and E. Riegler, "On the achievability of interference alignment in the K-user constant MIMO interference channel," in Proc. IEEE Workshop on Statistical Signal Processing (SSP), Cardiff, Wales, UK. Sept. 2009.

[20]. S. Ye and R.S. Blum, "Optimized signaling for MIMO interference systems with feedback," *IEEE Trans. Signal Processing*, vol. 51, no. 11, pp. 2839–2848, Nov. 2003. Y. Rong and Y. Hua, "Optimal power schedule for distributed MIMO links, *IEEE Trans. Wireless Comm.*, vol. 7, no. 8, pp. 2896–2900, Aug. 2008.