Performance Analysis of Optimum Combining under Multiple Primary Interferers in Underlay Cognitive Radio

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Submitted by

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DECLARATION

I, Rupinder Kaur, hereby, declare that the thesis "**Performance analysis of optimum combining under multiple primary interferers in underlay cognitive radio**" is an authentic record of my own work carried out towards the partial fulfillment for the award of degree of Master of Engineering in Wireless Communication at Thapar University, Patiala under the supervision of Dr.Surbhi Sharma, Assistant Professor, Electronics and Communication Engineering Department. The matter presented in this thesis has not been submitted in any other University/institute for the award of any other degree.

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Rupinder Kaur

ABSTRACT

Cognitive radio (CR) allows secondary users to share the same spectrum with primary users. The spectrum sharing should be carried out in such a way that the interference generated by the secondary user is held below a minimum threshold referred as interference temperature. The capacity of the Secondary user degrades due to this constraint .Therefore, to improve the performance of secondary user, diversity techniques can be used at the receiver of secondary user. Moreover, the performance of the secondary user is affected by the interference from the transmitter of primary user. Therefore, the diversity techniques should also be able to reduce the impact of interference in addition to reduce the fading.

In this dissertation work, the performance of underlay CR system is studied with optimum combining (OC) at the SU receiver under the impact of interference from multiple PU-Txs in flat Rayleigh fading channels. The number of primary user's transmitters L_t and antennas at SU receiver K_r are related as $L_t \geq K_r$. An expression is derived for the approximated probability density function of maximum SIR at secondary user receiver output. Using this density function, closed form expressions are obtained for the average post processing SIR, ergodic capacity ,outage probability and average bit error rate of the CR-OC system taking into consideration peak interference power constraint denoted as Q_p at primary user receiver. Performance of proposed system is compared with the maximal ratio combining in cognitive radio (CR-MRC). Analytical results for CR-OC system are validated through Monte Carlo simulations. Based on achieved results, it is shown that OC is significantly better than MRC even when the number of primary interferers exceeds the number of antennas at secondary user receiver. Also CR-OC with two more interferers gives the same performance as CR-MRC.

In order to achieve average bit error rate of 10^{-1} for L_t=3 for both the systems, CR-OC requires 5dB less power as compared to CR-MRC. In addition, with L_t=6, for an average bit error rate of $10^{-0.9}$, OC leads to a power saving of nearly 1.5dB over MRC.

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LIST OF ABBREVIATIONS

SU	Secondary User
PU	Primary User
CR	Cognitive Radio
SU-Rx	Secondary User’s Receiver
PU-Rx	Primary User’s Receiver
SU-Tx	Secondary User’s Transmitter
PU-Tx	Primary User’s Transmitter
SNR	Signal to noise ratio
SINR	Signal to interference plus noise ratio
SC	Selection Combining
MRC	Maximal Ratio Combining
EGC	Equal Gain Combining
OC	Optimum Combining
CDF	Cumulative Distribution function
PDF	Probability distribution function
BPSK	Binary Phase Shift Keying
BER	Bit Error Rate
FCC	Federal Communications Commission
DoT	Department of Telecommunications
SPTF	Spectrum Policy Task Force

TAS	Transmit Antenna Selection
MIMO	Multiple Input Multiple Output
CSI	Channel State Information

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Chapter1

INTRODUCTION

This chapter introduces cognitive radio systems and discusses their role in spectrum utilization. A brief explanation of diversity techniques is given which are used to improve the performance of spectrum sharing cognitive radio systems.

1.1 Evolution of Cognitive Radios

The part of the electromagnetic spectrum from 30Hz to 3000GHz is called radio spectrum. The waves in this frequency range known as radio waves are used in modern technology particularly for telecommunication purposes. The demand for radio spectrum has grown dramatically in recent years. This is due to increasing number of users, wireless applications and huge expansion in user expectations. This demand is expected to increase even more in the coming years. The different applications which make the use of radio spectrum are - fixed and mobile communications, audio and video broadcasting, railway, aviation, maritime transport, medical electronics, defense, emergency services, radio astronomy, remote control, space research as well as many others. To prevent the interference among all these services, radio spectrum is regulated by government agencies such as FCC in USA and DoT in India. According to traditional regulatory policy, most of the spectrum is exclusively licensed to users and transmitted power is limited in order to prevent the systems from mutual interference. This was the only option to protect the system from interference system in earlier years when the transmitters were not able to adapt their parameters and receivers were not robust towards intersystem interference. However, today with the progress in the transceiver design this approach has become an outdated policy.

As the most of the spectrum is already licensed, it is becoming uneasy to find the vacant spectrum to develop new applications and improve the existing applications. According to the reports presented by spectrum policy task force within the FCC, most of the parts of the radio spectrum remain unused or used very lightly for a significant period of time [1]. The bands allocated to the cellular networks are over laden everywhere, but the spectrum allocated to other services such as amateur ratio, military and paging services remain vacant for a long substantial period of time. Thus the shortage of spectrum is primarily due to the inefficient usage of the spectrum rather than the physical scarcity of spectrum.

SPTF proposed secondary access to licensed spectrum as a solution to mitigate the problem of spectrum scarcity. The existing user will be called as PU of the spectrum and new user will be called as SU of the spectrum. However, the spectrum sharing should be followed up in such a way so that the SU's communication does not cause interference to the PU's communication. The cognitive radio is introduced as an effective solution to deal with the problem of spectrum shortage. The cognitive radio concept, first introduced by Mitola [2] is an intelligent radio which is aware of its external environment, automatically detects the available radio spectrum and access best wireless channels which are not in use avoiding the channels which are already occupied. Cognitive radio is the evolution of the software defined radio. Software defined radio is a combination of hardware and software where the radio functions are implemented through software. Software defined radio is a radio transceiver which employs a technology that allows the radio frequency parameters such as frequency range, modulation type and output power to be modified by the software. CR allows the cognitive users to access the spectrum assigned to PUs as long as the interference generated by the SU-Tx is not harmful to the PU-Rx [3], [4].The spectrum sharing can be more effective if there are policies that support these forms of sharing. The policies which are inconsistent with forms of sharing will have a little impact [5].

There are mainly two types of cognitive radios depending upon the transmission and reception parameters.

1) **Full Cognitive Radio or Mitola radio**: Full CR considers the every possible parameter which is observable by a wireless node.
2) **Spectrum Sensing Cognitive Radio:** It only considers the radio frequency spectrum.

Depending upon the parts of spectrum available, some other types of cognitive radio are as follows

1) **Licensed Band Cognitive Radio:** In licensed band CR, the bands assigned to licensed users are utilized excluding unlicensed bands such as ISM band or U-NII band. The IEEE 802.22 working group is developing a standard for wireless local area network to operate in the TV white spaces i.e the unused part of the TV spectrum on a non-interference basis. The main motive is to provide broadband access to hard-to-reach rural areas. This technique has a great potential for applicability worldwide.

2) **Spectrum Mobility:** It is the process by which the CR user changes its operating frequency. CR allows the user to access best available wireless channel maintaining seamless communication and thus utilize the spectrum in a dynamic manner.
3) **Spectrum Sharing Cognitive Radio:** Spectrum sharing CR allows the CR users to share the same spectrum with PUs provided they do not cause any interference to the PU-Rx. Therefore the CR users have to limit their transmit power so that the interference generated to the licensed user is held under an acceptable threshold set at the receiver of the licensed user. The tolerable interference level at PU-Rx is defined as the interference temperature [6] or peak interference power constraint. The capacity under received power constraint was first studied in [7].
4) **Sensing-Based Spectrum Sharing:** In Sensing-based spectrum sharing, the CR users first sense the licensed user's band to detect the state of licensed users. If the licensed users are not transmitting over the bands, then CR user will transmit over those vacant bands.

According to the information available to CR system, there are mainly three CR paradigms-interweave, overlay and underlay [8], described in next section

1.2 Cognitive Radio Paradigms

1.2.1 Interweave Paradigm: This paradigm is based on the idea of opportunistic communication .This idea came after the FCC, universities [9], industry [10] stated that a major portion of the spectrum remain unused or used very lightly over a significant period of time. This leads to the existence of temporary space- time- frequency voids known as spectrum holes or white spaces. These spectrum holes are not in constant use for a long period of time in the licensed and unlicensed bands. These holes can be used by CR users for their own transmissions. Exploiting these spectrum holes, CR users operate in the orthogonal dimensions of space –time –frequency relative to non cognitive users [8] .Thus by using unused portion of the spectrum, spectrum utilization is increased. The interweave paradigm requires the knowledge of the information of non CR user's activities in the spectrum. CR user detects the primary user spectrum and can access the spectrum only if the non CR user is absent. Existing users are referred to as PUs whereas new users are referred to as SUs that can not cause any interference to the communications between existing users. Interweave paradigm can also be applied in network scenario where all the users in a given band have equal priority, but all the existing users are treated as PUs and new users as SUs and these users cannot interfere with the already existing communications between PUs.

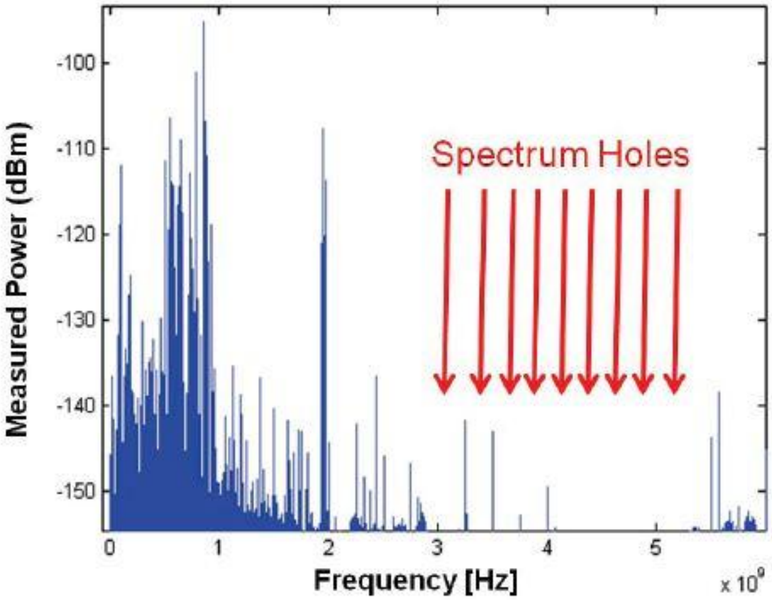

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Fig. 1 Measurement of spectrum holes upto 6-GHz at mid-day in urban area [8]

1.2.2 Overlay Paradigm: In overlay paradigm, it is assumed that the SU-Tx has information of the PU's transmitted data sequence also known as its message and encoding technique at PU-Tx, known as its codebook. The SU can obtain the PU's codebook information, for example, if the PU follows a uniform standard communication based on a publicized codebook. In addition to this, the PUs could broadcast their codebooks periodically. The knowledge of the PU's data and/or codebook can be utilized in different ways to either cancel or mitigate the interference seen at the primary and secondary receivers [8]. In addition to this, this information can be used to offset the interference caused due to the PU-Tx at SU-Rx. On the other hand, SU's can assign a part of their power for their own communication and the rest of the power to serve the PU's communications. By carefully dividing the power into two parts, the increase in the SINR of PU can be exactly offset by the decrease in the PU's SINR due to the interference generated by the part of the SU's power assigned to its own transmissions. The interference caused by the SU-Tx to PU-Rx can be partially or completely removed by modifying the PU-RX to decode both its data and all or part of the SU's data.

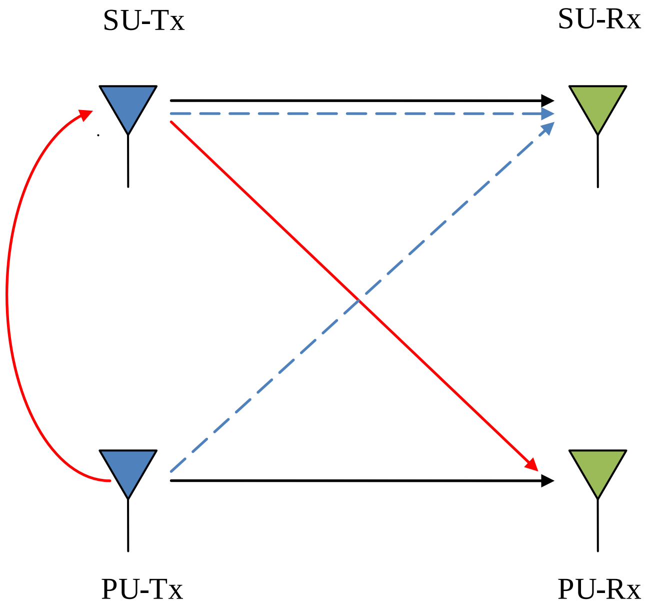

Fig. 1.2 The overlay paradigm [8]

To be successful, overlay systems has to face many problems. These include the overhearing of PU's data and encoding and decoding complexity at SU-Rx in these systems. Overhearing of primary data by SUs raises many security issues for the PU's data. However security issues can be overcome in some systems, especially when the data transmitted by PU is not private. For example, a cellular overlay within the TV broadcast spectrum. Overlay paradigm can be applied to both licensed an unlicensed bands. In licensed bands, the SUs are allowed to access the band because they would not cause any interference and assist in PU communication. In unlicensed band the SU's provide excellent spectrum utilization by exploiting the information of the PU's data and encoding techniques to reduce interference.

1.2.3 Underlay Paradigm: In underlay CR, the CR users simultaneously share the same spectrum with PU under the condition that the interference generated by CR user is held beneath a predefined limit at the PU-Rx also known as interference constraint. As a result, this constraint limits the communication range and transmission rate of the SU. An illustration of underlay CR is shown in fig. 1.3, where the SU shares the same spectrum with PU and the transmit power of the SU is kept below a predefined threshold at the PU-Rx. The interference temperature is defined as the maximum allowable interference in a particular frequency band, where the quality of service demand for the receiver can be satisfied. In order to access licensed band, the transmit power of the PU plus any other noise and interference should be kept below the interference temperature limit.

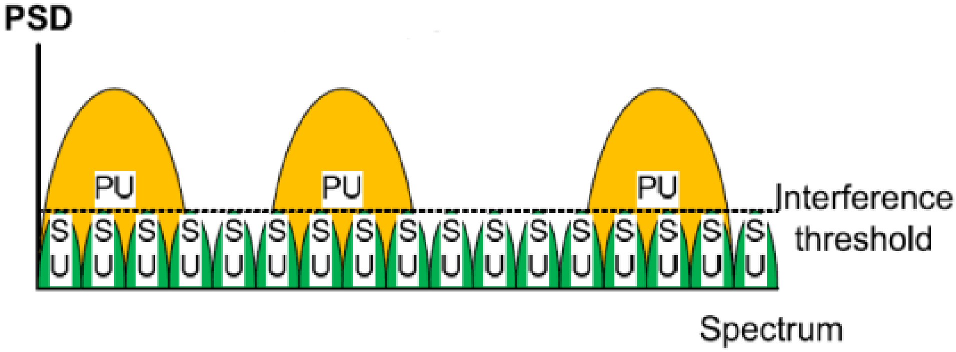

Fig. 1.3 The Underlay Paradigm [6]

If the SU is out of the coverage range of the PU, the SU can transmit with maximum power to improve its performance. Interference temperature is the measure of the radio frequency power at the receiving antenna and is given as [6]

$$T_I(f_c, B) = \frac{Q(f_c, B)}{kB} \tag{1.1}$$

where $Q(f_c, B)$ is the mean interference power in watts , f_c is the carrier frequency, B is the bandwidth in Hertz and $k = 1.28 \times 10^{-23}$ J/K is the Boltzmann constant.

1.3 Comparison of the Cognitive Radio Paradigms

The three different CR paradigms provide spectrum utilization by taking into consideration different parameters. The table below provides the difference between overlay, underlay and interweave paradigms on the basis of different parameters such as Network side information, simultaneous transmission, transmit power and hardware.

Table 1.1 Comparison of CR Paradigms

Overlay	Underlay	Interweave
Network Side Information SU has information about channel gains, encoding techniques and the data sequences transmitted by the PU.	**Network Side Information** SU-Tx has information about interference caused to PU-Rx.	**Network Side Information** SU detects spectrum holes in time, space, and/or frequency from which the PU is absent
Simultaneous Transmission SUs can transmit at same time as PUs. The interference to the PUs can be offset by assigning part of the SUs power to assist the PUs communication.	**Simultaneous Transmission** SUs can transmit concurrently with the PUs if the interference caused is below an predefined threshold.	**Simultaneous Transmission** SUs transmit concurrently with a PU only when there is missed detection of the PU activity.
Transmit Power Limits The SUs can transmit at any power. The interference caused to PUs can be cancelled by assisting the PUs transmission.	**Transmit Power Limits** The transmit power of SU's is limited by an interference constraint defined at the PU-Rx.	**Transmit Power Limits** SU's transmit power is bounded by the range of PU activity it can detect.
Hardware SUs overhear the PUs transmissions. Encoding and decoding complexity of overlay paradigm is also significantly higher than other paradigms.	**Hardware** SUs must have the knowledge of the interference caused to PU-Rx. It can be measured by utilizing channel reciprocity or by cooperative sensing.	**Hardware** Receiver must have a wideband front end for spectrum hole detection or it should be frequency agile.

1.4 Diversity Techniques

Diversity combining techniques are used to improve the performance of wireless communication systems in fading. Diversity combining removes the channel fluctuations due to fading and increases the reliability of the communication system. The diversity combining is based on the fact that all the independent signal paths have very low chances of undergoing deep fades simultaneously. The diversity combining techniques exploit the multipath .The same data is transmitted over independent multipath. These independent fading paths are combined in such a manner so that fading of the signal at combiner output is reduced. For example if multiple antennas are used at either transmitter or receiver, it is highly unlikely that all the antennas undergo deep fades [11]

The technique in which multiple antennas are used at either transmitter or receiver at a certain distance is called spatial diversity. With receive diversity combining all the antenna elements are devoted to a single user. The receive diversity does not require the increase in transmit power or signal bandwidth and the SNR achieved is greater than that obtained with a single antenna. With transmitter diversity, the transmitter power is divided among multiple antennas. Thus with coherent combining of the transmitted signals, the SNR achieved is same as that of a single transmit antenna. In spatial diversity it is required that the separation between antennas is such that the fading experienced by all antennas is independent. In receiver diversity, different antennas receive the different versions of the same signal. The chances that all these versions are in a deep fade are very small. Even if a single version has a reasonable power the signal can be processed adequately. All these versions are combined in such a manner that fading is reduced .Thus the diversity techniques can improve the signal to noise ratio at receiver of communication system. In diversity combining the signals received by different antennas are multiplied by a controllable weight and then combined to form the output signal.

There are three different forms of diversity combining-Selection combining, Equal gain combining and Maximal ratio combining. These three combining techniques differ in the choice of weight vector. The weight vector is chosen to minimize the effect of fading.

1.4.1 Selection Combining

In SC, the branch with highest SNR is selected for further processing. Therefore in SC, if the array has $K(k = 1, \dots. K)$ elements, then the weights can be given as

$$w_n = \begin{cases} 1, \gamma_n = \max_k(\gamma_k) \\ 0, \text{otherwise} \end{cases} \tag{1.2}$$

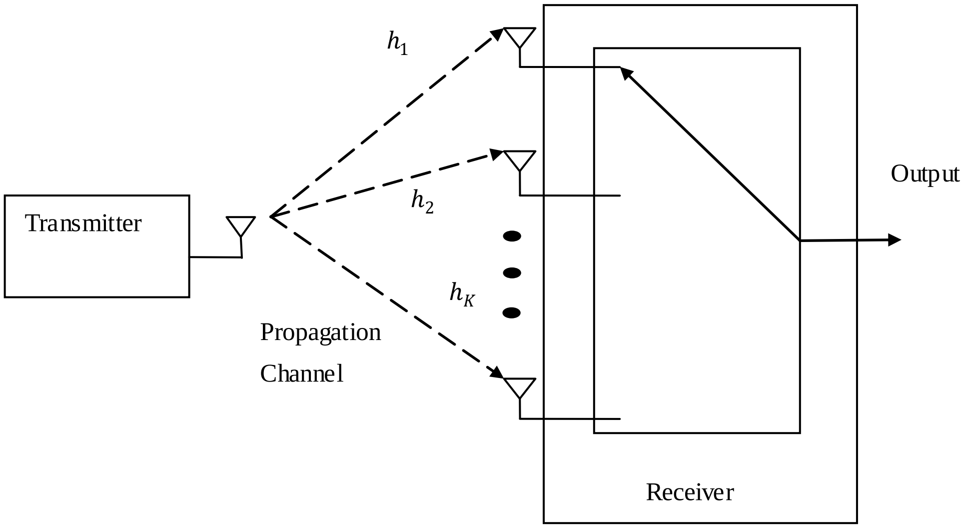

Fig.1.5 Selection Combining

Since the selected element has maximum SNR, therefore the output SNR of the SC technique is $\gamma = \max_k\{\gamma_k\}$ .Selection diversity technique only need a measurement of signal power .The phase shifters and variable gains are not needed in this technique.

1.4.2 Maximal Ratio Combining

The SC is not an optimal solution as it selects only one branch and ignores all other branches. In MRC all the branches are weighted in order to maximize the SNR at the combiner output. The branches with more SNR are weighted more than the branches having less SNR. Thus in MRC the weight is made proportional to the branch SNR. Thus in MRC, the output is a weighted sum of all branches. Therefore the MRC diversity is the optimal diversity technique from the standpoint of maximizing the SNR at the combiner output. The MRC weights are given as

$$w = h \tag{1.3}$$

where h is the channel gain vector .The SNR at combiner output is given by

$$\gamma = \sum_{k=0}^{K-1} \gamma_k \tag{1.4}$$

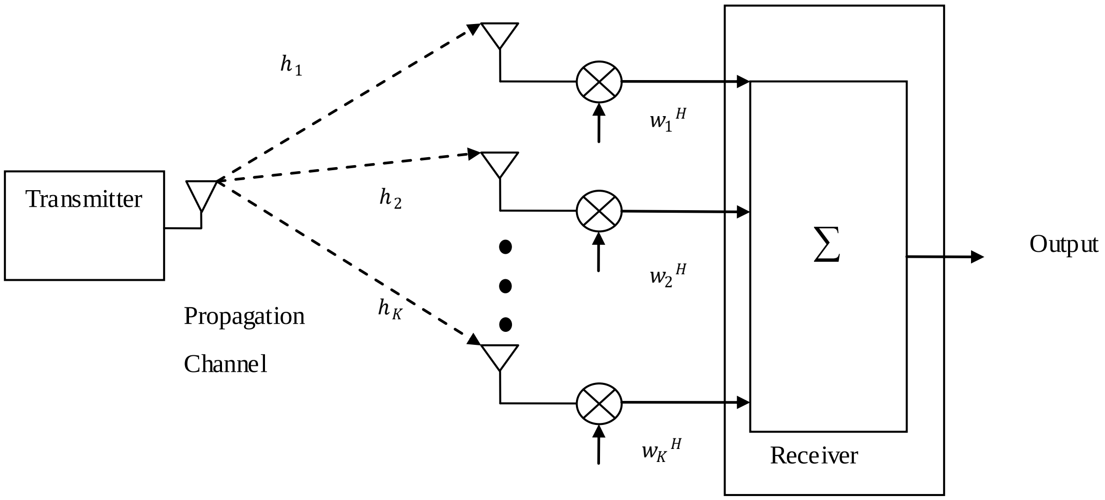

Fig. 1.6 Maximal Ratio Combining

1.4.3 Equal gain combining

In equal gain combining, unit gain is set at each antenna element. The signals received by each antenna elements are multiplied by an equal weight vector and are then combined to produce the array output. To avoid signal cancellation, the co-phasing of all signals is done. In comparison to MRC, EGC is simple to implement but provides 1dB less gain.

1.4.4 Optimum combining

The diversity techniques stated above maximize the SNR at the combiner output. The MRC diversity is optimum from the standpoint of maximizing the SNR in fading environment. However in addition to multipath fading, the performance of communication system is degraded by the interfering signals present. Thus in addition to reduce the fading, the diversity techniques should also be able to reduce the effect of interference present at each antenna element of the array. In interference environment, the best technique to use is the one which maximizes the SINR at the combiner output. In this scenario, the diversity technique named OC will give a greater SINR in comparison to MRC even when the interfering signals exceed the number of antenna elements [12]. The main difference between MRC and OC lies in the weight vectors. In MRC the weight vector is selected to maximize the SNR at the combiner output whereas in OC the weights are selected to maximize the signal to interference plus noise ratio at the combiner output. Considering a single interferer, the received signal at the output of antenna elements is given as

$$x(t) = \sqrt{P_t} h s(t) + \sqrt{P_I} h_I s_I(t) + n(t)$$

where $s(t)$ and $s_I(t)$ are desired and interfering signals respectively ,P_t and P_I are their corresponding powers and h and h_I are corresponding channel gain vectors. The received signal $r(t)$ after OC is

$$r(t) = w^H x(t)$$

The OC weights are given by [12]

$$w = \frac{h}{R_{ni}} \tag{1.5}$$

where R_{ni} is the noise plus interference covariance matrix defined as

$$R_{ni} = E\left\{\left(\sqrt{P_I} h_I s_I(t) + n(t)\right)\left(\sqrt{P_I} h_I s_I(t) + n(t)\right)^H\right\} = P_I h_I {h_I}^H + \sigma^2 I \tag{1.29}$$

where $\sigma^2$is the noise power. Therefore, the maximum instantaneous SINR at the output of the combiner is given by

$$\gamma = P_d h^H {R_{ni}}^{-1} h \tag{1.6}$$

when there is no interference, the performance of OC is similar to MRC.

$$\gamma = \frac{P_d}{\sigma^2} h^H h = \frac{P_d}{\sigma^2} \sum_{k=1}^{K} {\alpha_{dk}}^2 = \sum_{k=1}^{K} \gamma_k \tag{1.7}$$

where α_{dk} is the amplitude of fading element.

1.5 Diversity Techniques in Cognitive Radio Systems

In underlay spectrum sharing systems, the transmit power of SU is limited by the interference constraint at PU-Rx. Therefore the transmission range and capacity of spectrum sharing system becomes very low. The diversity techniques can be used at the SU- Rx to improve the performance of user spectrum sharing CR systems .The performance of SU is also affected by the interference from PU-Tx with which it is sharing spectrum. This interference can be reduced by employing OC technique. For a given interference constraint, the ergodic capacity increases when the antennas at SU-Rx are increased. From the above discussion, it is clear that OC is best diversity technique in interference channels. Therefore to reduce the impact of interference from PU-Tx, we can increase the number of SU-Rx antennas.

1.6 Thesis Organization

The different chapters of the thesis are organized as

Chapter 1: Introduction discusses about need of cognitive radio and describes different cognitive radio paradigms. It also discusses the need of diversity techniques in an underlay spectrum sharing system and explains different diversity schemes.

Chapter 2: **Literature Survey** briefs about the developments made in cognitive radios and the performance of diversity techniques in spectrum sharing cognitive radios.

Chapter 3: Gaps and Objectives present the research gaps and objectives the work under consideration.

Chapter 4: CR-OC System under Interference from Multiple PU-Txs describes system model of the spectrum sharing system. The average post processing SNR, ergodic capacity, average BER and outage probability of the system are described in this chapter.

Chapter 5: Results and Discussion presents analytical results of average post processing SIR, ergodic capacity, average BER and outage probability of the CR-OC system.

Chapter 6: Conclusion and Future Scope summarizes the results obtained from the proposed technique and discuss the possibility of future work.

Chapter 2

LITERATURE SURVEY

This chapter briefs about the developments made in cognitive radios, diversity techniques in underlay sharing systems and optimum combining technique.

J.M Peha [5] stated that the CR provides different forms of spectrum sharing if policies are in place that are consistent with different forms of sharing. The spectrum sharing techniques which are not consistent with spectrum policy have little impact. This paper discusses the spectrum policies that can ease use of many spectrum sharing arrangements which are based on co-operation or co-existence and as sharing among equal users and secondary primary sharing. Thus system designers must look for innovative ideas to ensure regulators that devices are consistent with policy requirements and will not cause any harmful interference.

M. Gastpar [7]: stated that the received power constraint is much more appropriate than the transmit power constraint. He investigated the capacity of spectrum sharing system under received power constraint modeling the interference that one system may cause to other system. It is concluded that in point to point systems, the transmit power constraint and interference power are equivalent while in network cases they provide different conclusions.

S. Haykin [13]: In this paper the interference temperature is discussed as a new metric for the quantification and management of interference. This paper discusses the emergent nature of the CR.

A. Ghasemi *et al.* [14] investigated the capacity gains offered by dynamic spectrum sharing system. The relation between SU capacity and interference imposed on PU-Rx is quantified. The capacity gains under different fading channels are compared and it is concluded that substantial capacity gains are achieved in fading environments as compared to the deterministic case.

A.J Goldsmith *et al.* [15] surveyed the fundamental capacity limits and associated transmission techniques for the different CR paradigms. The capacity is summarized in terms of lower and upper bounds for all three paradigms. This work also illuminates the increase in system degrees of freedom obtained through CRs. The guidelines are provided for the spectral efficiency gains achieved through CRs and practical ideas to mitigate the interference due to co-existence in CRs.

H.A Suraweera *et al.*[16] investigated the capacity of spectrum sharing system under imperfect channel state information between SU-Tx and PU-Rx .In addition to peak interference constraint at PU-Rx , a limit on the maximum transmit power is also defined. In case of imperfect CSI, the interference constraint cannot be satisfied and the SU-Tx has to back off its transmitting power.

R. Duan *et al*. [17] investigated the capacity of the spectrum sharing CR with MRC at SU-Rx in case of asymmetric fading. The channel between SU-Tx and PU-Tx follow Nakagami fading while the channel from SU-Tx to SU-Rx is Rayleigh faded. Results show that capacity of spectrum sharing CR can be increased through MRC diversity. If the fading between primary user receiver and secondary user transmitter is less severe, using MRC can reduce the effects.

R. Duan *et al*. [18] studied the capacity of spectrum sharing CR system with MRC diversity at SU-Rx in Rayleigh fading. The SU-Tx does not have the CSI of SU-Tx to PU-Rx link where the estimation error is taken into account. Mathematical results show that with MRC diversity at SU-Rx not only capacity is increased, but estimation error is also compensated.

D. Li [19] analyzed the impact of MRC diversity on the performance of spectrum sharing CR systems. The transmit power of the SU satisfies both transmit and interference power constraints. A CDF is derived for the received SNR. Using this CDF, analytical expressions are derived for the average symbol error rate and ergodic capacity of the considered system. Results show that using MRC full diversity order is achieved and shows the capacity scaling law as a function of number of SU-Rx antennas in case of the transmit power constraint dominating the transmit power of the SU.

V. Blagojevic [20] analyzed the spectrum sharing CR system with MRC diversity applied at SU-Rx under Nakagmi-m fading. Analytical expressions are derived for the ergodic capacity in case of average and peak interference constraints. It is shown that ergodic capacity of SU increases with the increase in the number of SU-Rx antennas. Ergodic capacity decreases for a larger number of antennas at PU-Rx. For higher values of fading factor the ergodic capacity is decreased. For higher values of interference constraints the effect of fading factors on the ergodic capacity of SU diminishes.

T.Q. Duong *et al.* [21] examined the impact of multiple PU transceivers on the outage probability of cognitive networks. The parameters taken into consideration are: peak received interference at the PU-Rx, maximum allowable transmit power of the SU-Tx) and interference at SU-Rx caused by the (PU-Tx). The expressions are obtained for the outage probability of the SU network. Based on these expressions, the effect of multiple PU-Txs on the SU relay network is studied. It is shown that when the peak received interference power constraint is independent of the maximum SU-Tx power, zero diversity order is attained.

Y. Huang *et al.* [22] studied the impact of the multiple primary transceivers on the outage probability of spectrum sharing systems with MRC in Rayleigh fading channel. A closed form expression is derived for the outage probability. It is found that system achieves zero diversity order and more stringent interference constraint results in more outage probability. This can be improved by using more SU-Rx antennas.

Y. Deng *et al.* **[**23**]** purposed the spectrum sharing CR with generalized selection combining at the receiver of SU under the interference from multiple PU-Txs and outdated channel information. The analysis take into consideration interference constraint and maximum transmit power of SU-Tx. Expressions are obtained for outage probability. These expressions represent the diversity order and the array gain. It is confirmed that the diversity order of generalized selection combining is fully dependent on the SU network and is equal to the number of SU-Rx antennas. This result is consistent with the results obtained using MRC and SC in spectrum sharing CR.

V.M. Bogachev *et al*. [24] analyzed the noise immunity for the space diversity reception in the presence of internal noise and noise from a single source in the receive antenna branches. Noise immunity of optimal space diversity is analyzed under the assumption that the parameters of the noise and signal are known.

J.H. Winters [25] studied the OC for the space diversity in cellular mobile radios. The signals are weighted and combined to maximize the SINR. In case of co channel interference space diversity reception is used not only to reduce the effect of multipath fading but also to reduce the power of the interfering signals. OC increases the output SINR by several decibels. Thus with OC, system require fewer number of base stations and hence capacity is increased through greater frequency reuse.

J. Cui *et al.* [26] presented the BER of the OC with two interferers and MRC with arbitrary number of interferes. In the first part, it is assumed that the channels are independent of each other. In the second part, the analysis of BER is done for the case of dominant interferes. An exact BER expression for BPSK is derived. In addition to this, an upper bound for BPSK or QAM signals is also presented.

A. Shah *et al.* [27] studied the performance of OC with multiple co-channel interferers in flat Rayleigh fading. The numbers of interfering signals are considered to be more than or equal to the receiver antennas. A PDF is obtained for the signal to interference ratio at the combiner. Using this PDF, closed form expressions are derived for the outage probability and average BER.

J.H Winters *et al.* [28] presented the upper bounds for the BER of OC with multiple co-channel interferers in a Rayleigh fading environment. Closed form expressions for the upper bound on the BER of the OC are derived for BPSK, QAM and DPSK schemes. Bounds on the performance gain of OC are also given over MRC. These bounds are tight for the decreasing value of the BER. The results show that the asymptotic gain is within 2dB of the gain as given by simulations. These expressions allow the calculation of the performance of OC under different conditions including the analysis of outage probability under the combined effect of adaptive arrays and dynamic channel assignment and shadow fading in mobile radio systems.

V. A. Aalo *et al.* [29] studied the impact of arbitrary number of co-channel interferers on the performance of digital mobile radio system under Nakagami fading. The closed form expressions are derived for the average BER for coherent and non-coherent BPSK in an interference environment..This paper also examines the effect of maximal ratio combining.

E. Villier [30] studied the OC under the impact of multiple equal power interferers for the case when number of receive antennas are more than the number of co-channel interferers. The desired signal and interfering signals undergo Rayleigh fading and independently distributed. An expression is derived for the probability density function of the SINR at the output of receiver which is then applied to obtain the CDF of the SINR and average bit error rate for some binary modulations. An exact analysis is done for the single interferer to validate the approximations.

V.A Aalo *et al*. [31] studied the impact of co-channel interference on the performance of digital mobile radio systems in Rayleigh fading environment. The average bit error rate of the system is analyzed with OC. The analytical expressions are derived for the coherent BPSK scheme in a co-channel interference and noise environment. The BER expressions are easy to evaluate numerically.

A. Shah *et al.* [32] obtained the analytical expressions for the exact BER for the detection of BPSK signal in case of OC for the case when desired signal and co-channel interferer are subjected to Rayleigh fading. The conditional BEP is averaged over the fading of the both signal and interference. Using alternative form of Gaussian- Q function, equations for BEP are derived using moment generating function method.

A. Shah *et al.* [33] compared the performance of cellular mobile radio system using three diversity techniques- MRC, EGC and OC. The problem under consideration is the detection of BPSK signal in the presence of multiple co-channel interferers having equal power. The signal of interest is assumed to be Rayleigh and interfering signals are assumed to be Rice faded. For EGC, the expression is derived for the mean SIR for Rayleigh and Rice fading. For MRC, the expressions are obtained for average outage probability and average BER in case of Rayleigh and Rician fading and for OC in case of Rician fading. The analytical results obtained for MRC hold for an arbitrary number of antennas while in case of OC the number of interfering signals are greater than or equal to the number of receive antennas.

M. Chiani *et al.*[34] derived a closed form expression for the SEP in case of M-ary phase shift keying using OC in Rayleigh fading environment. The analysis is based on the theory of orthogonal polynomials. The interferers are assumed to be of equal power. Effect of thermal noise is also considererd. The result is valid for an arbitrary number of receive antennas and/or co-channel interferers. The results obtained are useful for the design of wireless communication systems.

C. Chayawan *et al.* [35] analyzed the performance of MRC and OC with Rician fading and co-channel interference. The expressions are derived for the PDF and outage probability for MRC and OC in case the signal undergo rician fading and interference are assumed to be at a large distance from the receiver. The interferers are assumed to be of equal power and the number of interferers are greater than the number of receive antennas.

D. Lao *et al.* [36] obtained the new expressions for the bit error probability and symbol error probability in case of M-ary phase shift keying. These expressions are valid for any number of interferers and receive antennas. Both the desired and interfering signals are assumed to be subjected to Rayleigh fading. The expressions obtained were having very low complexity.

D. Lao *et al.* **[**37**]** derived a closed form expressions for the exact BEP for OC in case of BPSK scheme. The exact BEP expression is derived for multiple, equal power, co-channel interferers and multiple diversity branches. The desired signal and interfering signals are subject to Rayleigh fading. The interference and noise are Gaussian. The BEP expression has very low complexity.

D.Lao *et al*. [38] derived the new expression for the average symbol error probability for OC with M-ary phase-shift keying. The expression is valid for interferers with arbitrary power. The expression is very less complex. A closed-form expression for the average symbol error probability in case of BPSK is also derived.

Chapter 3

GAPS AND OBJECTIVES

In this chapter on the basis of literature survey research gaps and objectives of our study have been framed.

3.1 Research Gaps

In the literature, the diversity techniques are studied to improve the performance of spectrum sharing systems. Diversity techniques are employed at the SU-Rx to increase the capacity of the SU. Many research gaps have been observed which are as follows

1) The analysis of spectrum sharing system is done using MRC, SC and GSC. But these techniques are not optimal from the standpoint of minimizing the power of the interfering signals.
2) The most of the work considered does not take into account the impact of the PU on the performance of SU.
3) The OC technique is optimum from the standpoint of maximizing the SINR at the combiner output. But the spectrum sharing system with OC is not explored well.

3.2 Objectives

1) To simulate the MRC diversity technique in underlay cognitive radio.
2) To simulate the OC diversity technique in underlay cognitive radio.
3) To analyze the OC technique in underlay spectrum sharing cognitive radios to reduce the impact of interference from the multiple PU-Txs
4) To compare OC technique with the MRC technique in cognitive radios terms of average post processing SIR, ergodic capacity, average bit error rate and outage probability.

Chapter 4

CR-OC SYSTEM UNDER INTERFERNCE FROM MULTIPLE PRIMARY TRANSMITTERS

This chapter presents the system model of the underlay CR system with OC at the SU-Rx (CR-OC) under the impact of the interference from multiple primary user transmitters in flat Rayleigh fading environment. The analytical results are presented for average post processing SIR, ergodic capacity, average BER and outage probability of the CR-OC system.

4.1 System Model

The system under consideration is an underlay CR system which is demonstrated in Fig. 4.1.It comprises a SU-Tx, a SU-Rx, a PU-Rx and $L_t(l = 1, \ldots, L_t)$ PU-Txs .The SU-Rx and PU-Rx are employing $K_r(k = 1, \ldots, K_r)$and $M_r(m = 1, \ldots, M_r)$ antennas, respectively. The SU shares the same spectrum with the primary network. The signals of the PU-Txs cause interference to the SU-Rx. The SU-Tx and PU-Tx employ single antenna each. The peak interference power constraint, which represents the maximum received interference power at PU-Rx is denoted by Q_p. Let g_s be the $(1 \times K_r)$ channel vector between SU-Tx and SU-Rx, h_s be the $(1 \times M_r)$ channel vector from SU-Tx to PU-Rx and h_{p_l}be the $(1 \times K_r)$ channel vector between l^{th} PU-Tx and SU-Rx.

The entries g_{s_k},h_{s_m} and $h_{p_{lk}}$of g_s, h_s and $h_{p_l}$are independent and identically distributed (i.i.d) exponential random variables, respectively. The bandwidth of the system is normalized to 1 and is denoted as B. The number of PU-Txs is assumed to be more than the numbers of SU-Rx receive antennas. Therefore, the thermal noise is neglected as the array degrees of freedom are insufficient to null all the interfering sources [27].The SU-Tx employs BPSK modulation. Assuming that the SU-Tx has perfect CSI from SU-Tx to PU-Rx link, the maximum permissible transmit power P_t of SU-Tx at each instant is given by [20]

$$P_t = \frac{Q_p}{h_s} \tag{4.1}$$

where $h_s = \sum_{m=1}^{M_r} h_{s_m}$ is a Chi-Square distributed random variable with $2M_r$ degrees of freedom and PDF of h_s is given by

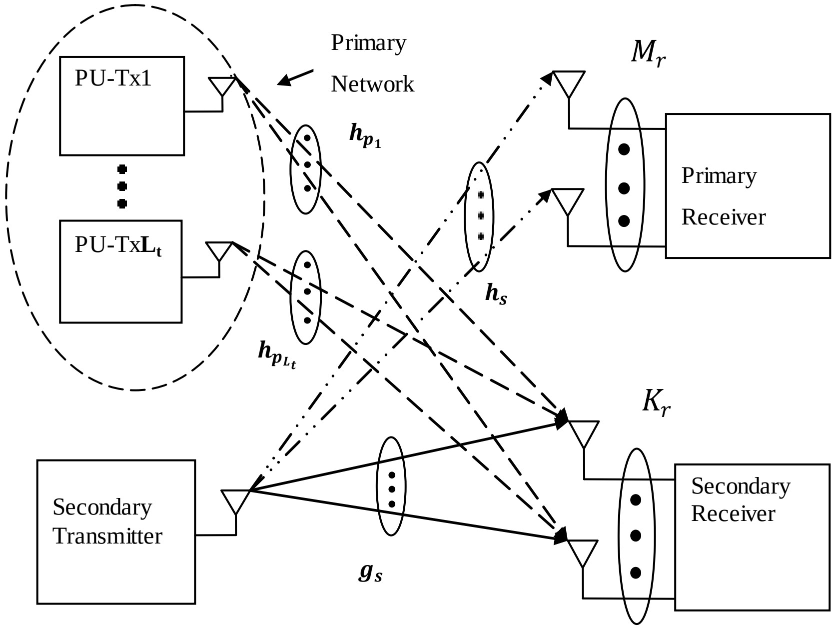

Fig. 4.1 System Model of CR-OC system.

$$f_{h_s}(h_s) = \frac{1}{\Gamma(M_r)} {h_s}^{M_r-1} e^{-h_s} \tag{4.2}$$

where Γ is the standard Gamma function and is given as $\Gamma(\alpha) = (\alpha - 1)!$.

To improve the performance of the system OC is employed at SU-Rx to maximize the SIR. Considering the interference from all PU-Txs, the combined received signal Y_s at SU-Rx can be given as

$$Y_s = w^H \sqrt{P_t}\, g_s x_s + w^H \sum_{l=1}^{L_t} \sqrt{P_l} h_{p_l} x_{p_l} \tag{4.3}$$

where x_s is the signal to be transmitted by SU-Tx and x_{p_l} is the signal of l^{th} PU-Tx. P_l is the power of l^{th} PU-Tx .All the channel coefficients have zero mean and σ^2 variance. The covariance matrix of h_{p_l} is $\epsilon_{cov} = E[h_{p_l} {h_{p_l}}^H]$.The number of receive antennas at SU-Rx and interfering signals are related as $L_t \geq K_r$.The power of each interfering signal is assumed to be same. The OC weight vector that maximizes the SIR at the SU-Rx output is given by [25]

$$w = R^{-1} g_s \tag{4.4}$$

where R is the interference covariance matrix and is given by

$$R = \sum_{l=1}^{L_t} P_l h_{p_l} h_{p_l}^H \tag{4.5}$$

where superscript H represents the complex conjugate transpose. The covariance matrix R is assumed to vary with the fading rate. The fading rate is assumed to be very small than the bit rate.

The main contributions of this work are

1) An expression is derived for the approximated PDF of SIR at SU-Rx of CR-OC system.
2) Utilizing this PDF, a closed form expression is derived for the average post processing SIR, ergodic capacity, average BER and outage probability of the CR-OC system.
3) The analytical results for MRC are obtained.
4) The CR-OC system is then compared with CR system employing MRC (CR-MRC) system.

4.2 Performance Analysis

In this section using the results of previous section, an approximate PDF is derived for the SIR of CR-OC system by considering interference from equal power multiple PU-Txs. Using this PDF, the analytical expressions are obtained for the average post processing SIR, ergodic capacity, outage probability and average BER for the CR-OC system in flat Rayleigh Fading .

4.2.1 PDF of Maximum SIR

From (4.1) and (4.3), the SIR γ_s at the output of SU-Rx can be given by

$$\gamma_s = P_t {g_s}^H R^{-1} g_s = \frac{Q_p}{h_s} {g_s}^H R^{-1} g_s \tag{4.6}$$

For the case of equal power interferers, let $R = PR_1$,where $R_1 = \sum_{l=1}^{L_t} h_{p_l} h_{p_l}^H$ and P is the power of all PU-Txs Therefore, γ_s in (4.6) becomes

$$\gamma_s = \frac{Q_p}{h_s P} {g_s}^H {R_1}^{-1} g_s = \frac{Q_p}{h_s P} z \tag{4.7}$$

where $z = {g_s}^H {R_1}^{-1} g_s$ and its PDF is given by [27]

$$f_z(z) = \frac{\Gamma(L_t+1)}{\Gamma(K_r)\Gamma(L_t+1-K_r)} \frac{z^{K_r-1}}{(1+z)^{L_t+1}} \tag{4.8}$$

$$z \geq 0, 1 \leq K_r \leq L_t$$

The PDF in (4.8) is a modified form of central F Distribution. The density of the z does not depend upon the form of the covariance matrix ϵ.Thus the performance of the OC is same regardless whether the fading at each receive antenna is independent or not. However, this is true only for the case $L_t \geq K_r$.

Since F Distribution can be converted into Chi-Square distribution [39], therefore (4.8) can be rewritten as

$$f_z(z) = \frac{(L_t+1-K_r)^{K_r}}{\Gamma(K_r)} z^{K_r-1} e^{-(L_t+1-K_r)z} \tag{4.9}$$

In (4.7), let us substitute

$$\mu = \frac{z}{h_s} \tag{4.10}$$

$$\beta = h_s \tag{4.11}$$

Using (4.2) and (4.9), the marginal pdf for the division of z and h_s is evaluated as [40]

$$f_\mu(\mu) = \frac{(L_t+1-K_r)^{K_r}}{\Gamma(M_r)\Gamma(K_r)} \mu^{K_r-1} \frac{(K_r+M_r-1)!}{[(L_t+1-K_r)\mu+1]^{K_r+M_r}} \tag{4.12}$$

Therefore $f_\mu(\mu)$ is the final approximate PDF for the SIR at the SU-Rx output in CR-OC system and is plotted in fig. 4.2.The figure shows that the SIR will take larger values when the number of SU-Rx receive antennas are increased.

4.2.2 Average Post Processing SIR

Since the first moment of μ can be given by

$$E\{\mu\} = \int_0^\infty \mu f_\mu(\mu)\, d\mu$$

$$= \int_0^\infty \mu \frac{(L_t+1-K_r)^{K_r}}{\Gamma(M_r)\Gamma(K_r)} \mu^{K_r-1} \frac{(K_r+M_r-1)!}{[(L_t+1-K_r)\mu+1]^{K_r+M_r}}$$

$$= \frac{\Gamma(M_r-1)\Gamma(K_r+1)}{\Gamma(K_r)\Gamma(M_r)(L_t+1-K_r)} \tag{4.13}$$

The average post processing SIR at the output of the SU-Rx of the CR–OC system is given as follows

$$E\{\gamma_s\} = \frac{Q_p}{P} \frac{\Gamma(M_r-1)\Gamma(K_r+1)}{\Gamma(K_r)\Gamma(M_r)(L_t+1-K_r)} \tag{4.14}$$

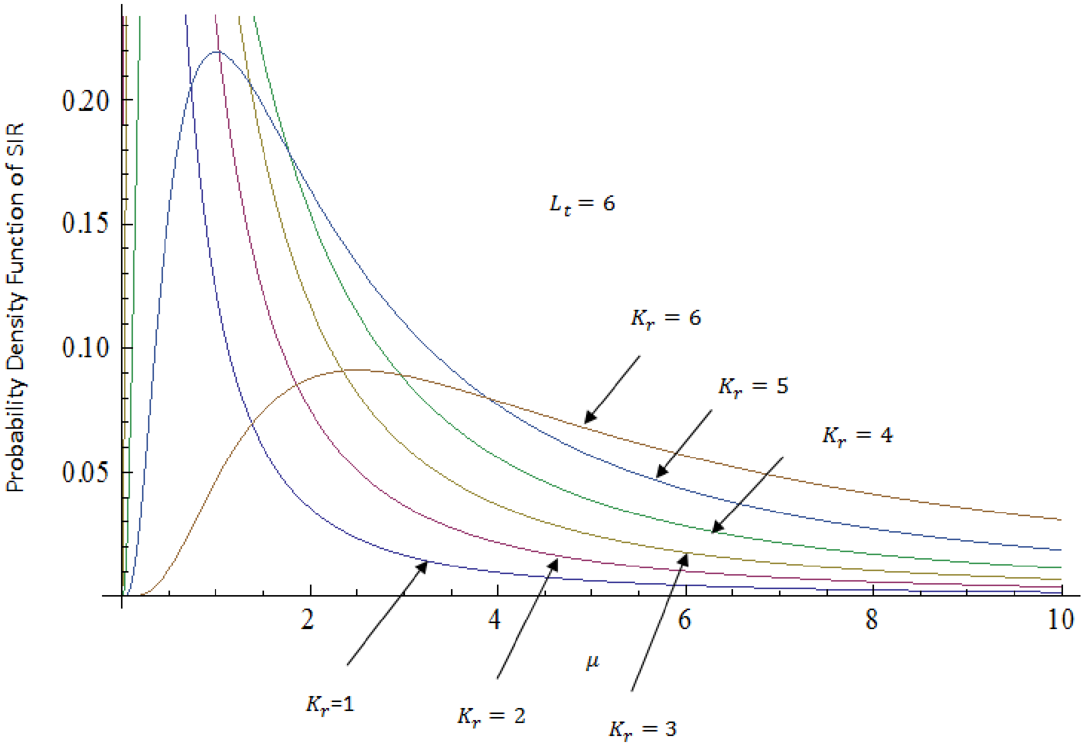

Fig. 4.2 The effect of number SU-Rx antennas on probability density function of SIR μ

4.2.3 Ergodic Capacity

The ergodic capacity of SU link under PU interference constraint is defined as the maximum long term achievable rate and is obtained by averaging the channel capacity over $f_\mu(\mu)$ .From (4.7) and (4.10), $\gamma_s = \mu Q_p/P$, therefore, the ergodic capacity C_{CR-OC} of the CR-OC system is given by

$$C_{CR-OC} = \int_0^\infty log_2\left(1+\mu\frac{Q_p}{P}\right) f_\mu(\mu)\, d\mu$$

$$= \frac{(L_t+1-K_r)^{K_r}}{\Gamma(K_r)\Gamma(M_r)}(K_r+M_r-1)!\int_0^\infty \frac{log_2\left(1+\mu\frac{Q_p}{P}\right)\mu^{K_r-1}}{[(L_t+1-K_r)\mu+1]^{K_r+M_r}}d\mu \tag{4.15}$$

By further solving (4.15), we get

$C_{CR-OC} =$

$$\frac{(K_r+M_r-1)!}{\Gamma(K_r)\Gamma(M_r)}\sum_{a=0}^{K_r-1}\binom{K_r-1}{a}(-1)^{K_r-1-a}\frac{1}{\log(2)}\frac{1}{(K_r+M_r-a-1)^2}\times {}_2F_1\left(1, K_r+M_r-a-1; K_r+M_r-a, ; \frac{K_r-L_t+\frac{Qp}{P}-1}{\frac{Qp}{P}}\right) \tag{4.16}$$

where ${}_2F_1$ is hypergeometric function and is defined as[41]

$$ {}_2F_1(c,d;e;\zeta) = \sum_{i=0}^{\infty} \frac{(c)_i (d)_i}{(e)_i} \frac{\zeta^i}{i!} \tag{4.17} $$

Hence, (4.17) is the final expression of the ergodic capacity of the puposed system .

4.2.4 Outage Probability

Outage probability is an important statistical measure in the design of spectrum sharing system in fading environment with interference from PUs. It is the probability of unsatisfactory reception over the intended coverage area. The outage probability is the probability that the SIR is below a given threshold sufficient to achieve radio reception in fading environment. It is expressed as

$$ \begin{aligned} P_{outage} &= \text{Probability}(\gamma_s < \gamma_0) \\ &= \int_0^{\gamma_0} f_{\gamma_s}(\gamma_s) d\gamma_s \end{aligned} \tag{4.18} $$

where γ_0 is the SIR protection ratio. Its value depends on the modulation technique used and also on the desired performance [27]. It is also known as cumulative distribution function.

From (4.7) and (4.10),γ_s=$\frac{Q_p}{P}\mu$. Therefore the PDF of γ_s can be obtained by substituting $\mu = \frac{\gamma_s P}{Q_p}$ into (4.12) and is given by

$$ f_{\gamma_s}(\gamma_s) = \frac{(K_r + M_r - 1)!}{\Gamma(K_r)\Gamma(M_r)} \left(\frac{Q_p}{P(L_t + 1 - K_r)} \right)^{K_r} \frac{{\gamma_s}^{K_r - 1}}{\left(\gamma_s + \frac{Q_p}{P(L_t + 1 - K_r)} \right)^{K_r + M_r}} \tag{4.19} $$

Using (4.18), the P_{outage} is expressed as

$$ P_{outage} = \int_0^{\gamma_0} \frac{(K_r + M_r - 1)!}{\Gamma(K_r)\Gamma(M_r)} \left(\frac{Q_p}{P(L_t + 1 - K_r)} \right)^{K_r} \frac{{\gamma_s}^{K_r - 1}}{\left(\gamma_s + \frac{Q_p}{P(L_t + 1 - K_r)} \right)^{K_r + M_r}} d\gamma_s $$

$$ = \frac{(K_r + M_r - 1)!}{\Gamma(K_r)\Gamma(M_r)} \left(\frac{Q_p}{P(L_t + 1 - K_r)} \right)^{K_r} \int_0^{\gamma_0} \frac{{\gamma_s}^{K_r - 1}}{\left(\gamma_s + \frac{Q_p}{P(L_t + 1 - K_r)} \right)^{K_r + M_r}} d\gamma_s $$

$$ = \frac{(K_r + M_r - 1)!}{K_r \Gamma(K_r)\Gamma(M_r)} \left(\frac{Q_p}{P(L_t + 1 - K_r)} \right)^{-K_r} {\gamma_0}^{K_r} \frac{{}_2F_1\left(K_r, K_r + M_r, K_r + 1, \frac{(K_r - L_t - 1) P \gamma_0}{Q_p} \right)}{K_r} \tag{4.20} $$

4.2.5 Average Bit Error Rate

The average BER is an important performance indicator of CR-OC system. In this section, the average BER of CR-OC system is derived under peak interference power constraint denoted as Q_p. For BPSK modulation, the probability of error calculated at a given value of γ_s, in terms of Gaussian-Q function is given by

$$P_{e|\gamma_s} = Q\left(\sqrt{2\gamma_s}\right) \tag{4.21}$$

Therefore, the average BER of CR-OC system is obtained by integrating (4.21) over $f_\mu(\mu)$ and is given by

$$P_{e_{CR-OC}} = \int_0^\infty Q\left(\sqrt{2\mu\frac{Q_p}{P}}\right) f_\mu(\mu) d\mu \tag{4.22}$$

The Q-function and complementary error function are related as

$$Q\left(\sqrt{2\gamma_s}\right) = \frac{1}{2} erfc\left(\sqrt{\gamma_s}\right) \tag{4.23}$$

The average BER of CR-OC system is obtained as

$$P_{e_{CR-OC}} = \frac{1}{2}\int_0^\infty erfc\left(\sqrt{\mu\frac{Q_p}{P}}\right) f_\mu(\mu) d\mu \tag{4.24}$$

$$= \frac{1}{2}\frac{(L_t+1-K_r)^{K_r}}{\Gamma(M_r)\Gamma(K_r)}(K_r + M_r - 1)! \int_0^\infty erfc\left(\sqrt{\mu\frac{Q_p}{P}}\right) \times \frac{\mu^{K_r-1}}{[(L_t+1-K_r)\mu+1]^{K_r+M_r}}\, d\mu \tag{4.25}$$

The above expression can be evaluated as

$$= \frac{1}{2\Gamma(M_r)\Gamma(K_r)}\left[\Gamma(M_r)\Gamma(K_r) - \frac{2\sqrt{\frac{Q_p}{P}}\Gamma\left(\frac{-1}{2}+M_r\right)\Gamma\left(\frac{1}{2}+K_r\right)\ {}_pF_q\left(\frac{1}{2},\frac{1}{2}+K_r;\frac{3}{2},\frac{3}{2}-M_r;\frac{Q_p}{P(L_t+1-K_r)}\right)}{\sqrt{\pi(L_t+1-K_r)}}\right.$$
$$\left. - \frac{(L_t+1-K_r)^{-M_r}\left(\frac{Q_p}{P}\right)^{M_r}\Gamma\left(\frac{1}{2}-M_r\right)\Gamma(K_r+M_r)\ {}_pF_q\left(M_r, M_r+K_r;\frac{1}{2}+M_r, M_r+1;\frac{Q_p}{P(L_t+1-K_r)}\right)}{M_r\sqrt{\pi}}\right] \tag{4.26}$$

where ${}_pF_q$ is the generalized hypergeometric function and has series expansion[41]

$${}_pF_q(c;d;\zeta) = \sum_{i=0}^\infty \frac{(c_1)_i\ldots(c_p)_i}{(d_1)_i\ldots(d_q)_i}\frac{\zeta^i}{i!} \tag{4.27}$$

Hence, (4.27) is the final expression for the average BER of CR-OC system.

Chapter 5

RESULTS AND DISCUSSION

In this chapter, analytical results are presented for the CR-OC system under the impact of interference from multiple PU-Txs in flat Rayleigh fading environment. The analytical results for CR-MRC system are also presented.This chapter also provides comparison between CR-OC and CR-MRC system on the basis of different performance parameters.

5.1 CR-OC system

In this section, using the analysis presented in chapter 4, we obtain the curves for the average post processing SIR, ergodic capacity, average BER and outage probability of the CR-OC system. Analytical results for ergodic capacity and average BER are validated through simulations. Here, we assume that the transmit power P_l of each PU-Tx is 10dB and number of PU-Rx antennas M_r=1, unless otherwise specified.

5.1.1 Average Post Processing SIR

The average post processing SIR of the CR-OC system versus Q_p as a function of number of PU-Txs is shown in fig.5.1. Here we assume the number of PU-Rx antennas M_r=2.

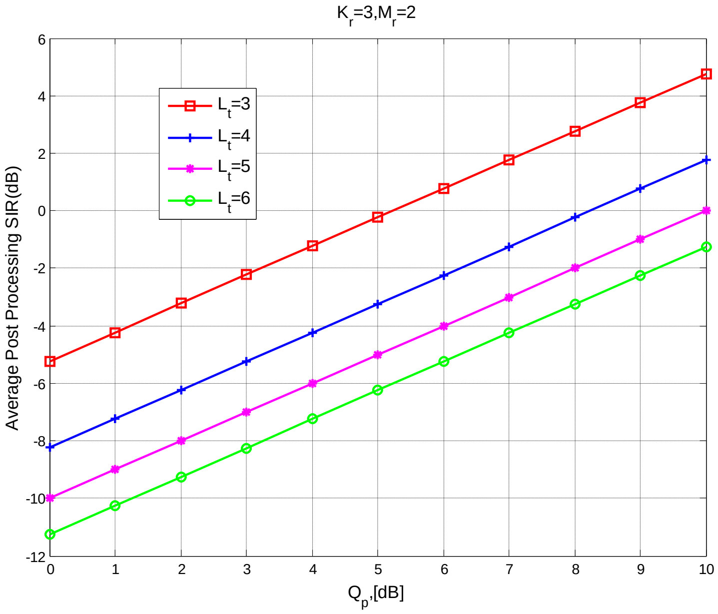

Fig.5.1 Average post processing SIR of the CR-OC system versus Q_p as a function of number of PU-Txs L_t.

Table 5.1 Average post processing SIR values for CR-OC obtained by varying L_t

<table>
<tr><th rowspan="2">Parameter</th><th colspan="8">Number of PU-Txs L_t</th><th rowspan="2">Notes</th></tr>
<tr><th colspan="2">L_t=3</th><th colspan="2">L_t=4</th><th colspan="2">L_t=5</th><th colspan="2">L_t=6</th></tr>
<tr><td>Average Post Processing SIR(dB)</td><td colspan="2">-0.23</td><td colspan="2">-3.23</td><td colspan="2">-5</td><td colspan="2">-6.25</td><td rowspan="2">Q_p=5dB, P_I=10dB, K_r=3, M_r=2</td></tr>
<tr><td>SIR Loss (dB)</td><td colspan="3">3</td><td colspan="3">1.77</td><td colspan="2">1.25</td></tr>
</table>

It is seen that increasing the number of PU-Txs degrades the performance of the system. The average post processing SIR values for different number of PU-Txs is shown in table 5.1. It is concluded that with the further increase in the number of PU-Txs, the fall in the average post processing SIR becomes small.

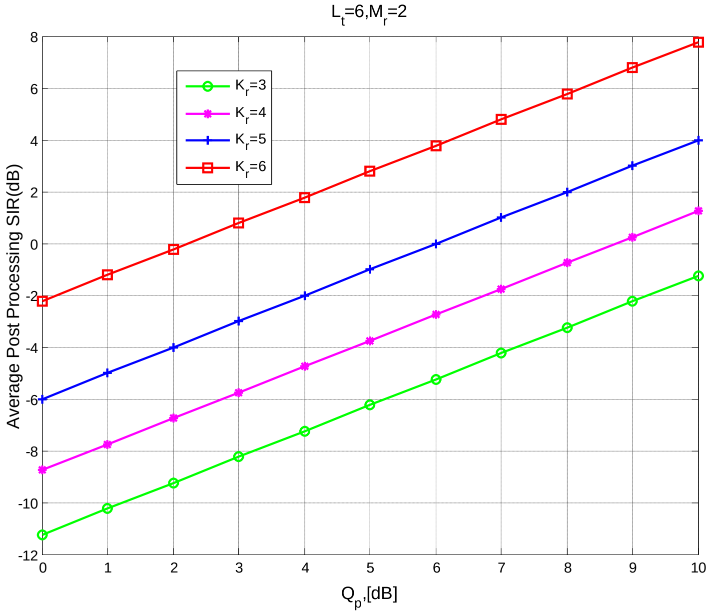

Fig.5.2 Average post processing SIR for the CR-OC system versus Q_p with K_r as parameter

The performance of the average post processing SIR versus Q_p for different number of SU-Rx antennas is shown in fig. 5.2 The gain in the average post processing SIR increases as the number of receive antennas are further increased. The average post processing SIR of CR- OC system for different number of SU-Rx receive antennas and gain achieved by increasing antennas is shown in table 5.2.

Table 5.2 Average post processing SIR for CR-OC system obtained by varying K_r

Parameter	Number of SU-Rx antennas				Notes
	K_r=3	K_r=4	K_r=5	K_r=6	
Average Post Processing SIR(dB)	-6.25	-3.75	-1.02	2.78	Q_p=5dB,P_I=10dB, L_t=6, M_r=2
SIR Gain	2.5	2.7	3.8		

The SIR gain achieved when the numbers of antennas are increased from 3 to 4 is 2.5dB, 4 to 5 is 2.7 dB and when numbers of SU-Rx antennas are increased from 5 to 6, the SIR gain achieved is 3.8dB.

5.1.2 Ergodic Capacity

The results of ergodic capacity for the CR-OC system are shown in fig. 5.3. With the increase in the number of PU-Txs, the ergodic capacity of the system degrades. The ergodic capacity of the CR-OC system with L_t=3 is 1.56 bits/s/Hz, L_t=4 is 1.07 bits/s/Hz, L_t=5 is 0.84 bits/s/Hz and with L_t=6 is 0.71bits/s/Hz at Q_p=5dB, respectively.

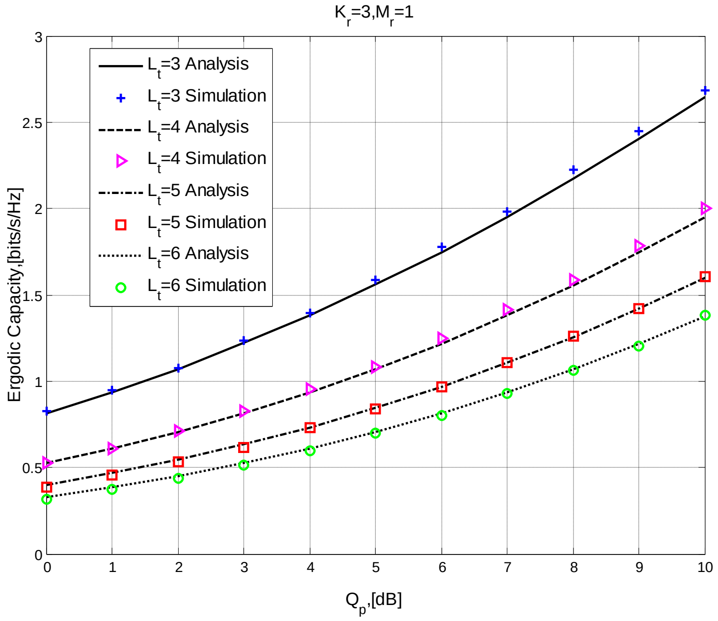

Fig. 5.3 Ergodic capacity of the CR-OC system versus Q_p for different number of PU-Txs L_t.

From the figure, we observe that the ergodic capacity of the CR-OC system improves when Q_p increased i.e the received interference power constraint at PU-Rx is is increased which further allows SU-Tx to transmit with increased power. Table 5.3 shows the ergodic capacity loss due to the increasing number of PU-Txs.

Table 5.3 Ergodic capacity values of CR-OC system obtained by varying L_t

Parameter	Number of PU-Txs L_t				Notes
	L_t=3	L_t=4	L_t=5	L_t=6	
Ergodic Capacity (bits/s/Hz)	1.56	1.07	0.84	0.71	Q_p=5dB, P_I=10dB, K_r=3, M_r=1
Capacity Loss (%)	31%		21%	15%	

Fig. 5.4 shows the ergodic capacity of the CR-OC versus Q_p for different number of SU-Rx antennas. The ergodic capacity increases when the antennas at SU-Rx are increased. The ergodic capacity of the CR-OC system for K_r=3 is 0.70bits/s/Hz, for K_r=4 is 1.01 bits/s/Hz, for K_r=5 is 1.45 bits/s/Hz and for K_r=6 is 2.23 bits/s/Hz at Q=5dB.

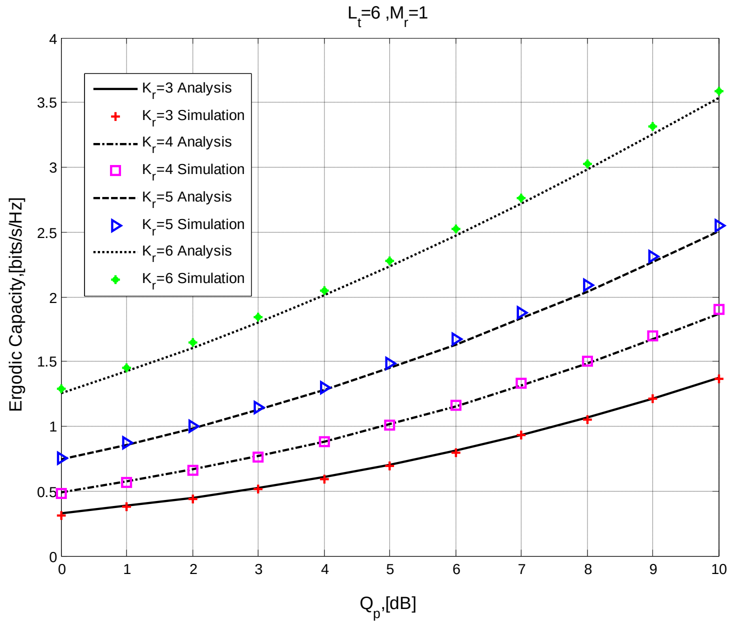

Fig.5.4 Ergodic capacity of the CR-OC system versus Q_p for different number of SU-Rx antennas K_r

From Table 5.4, we can see that the gain in ergodic capacity when number of SU-Rx antennas are increased from 3 to 4 is 44%, from 4 to 5 is 45% and when SU-Rx antennas are increased from 5 to 6 ,the ergodic capacity gain becomes much greater and is 54%.

Table 5.4 Ergodic capacity values for CR-OC system obtained by varying K_r

Parameter	Number of SU-Rx antennas				Notes
	K_r=3	K_r=4	K_r=5	K_r=6	
Ergodic Capacity (bits/s/Hz)	0.70	1.01	1.45	2.23	Q_p=5dB,P_I=10dB, L_t =6, M_r=1
Capacity Gain (%)	44%	45%	54%		

5.1.3 Average BER

The outcomes of average BER for the CR-OC system are demonstrated in fig. 5.5. As it is clear that when interfering sources are increased, the average BER performance of the system degrades, hence the average BER at L_t=3, 4, 5 and 6 is 0.09, 0.14, 0.18 and 0.20, at Q_p=5dB, respectively. Increase in the value of Q_p leads to an improvement in average BER of the CR-OC system.

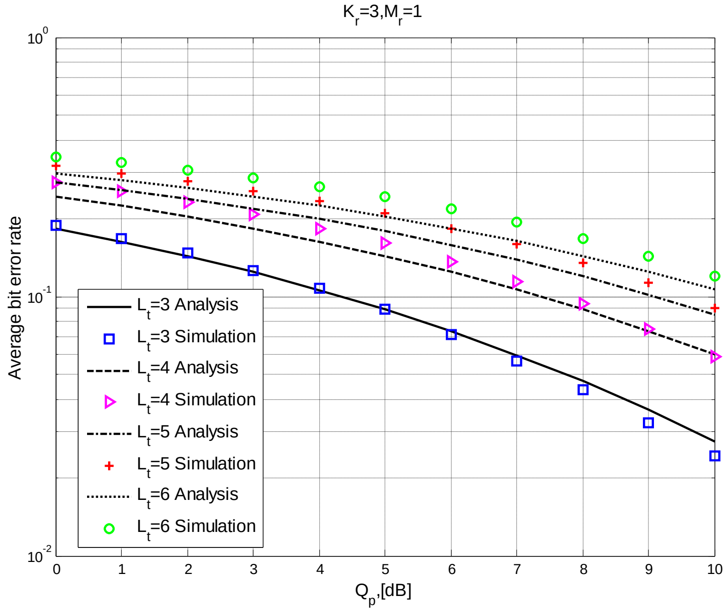

Fig. 5.5 Average BER of the CR-OC system versus Q_p for different number of PU-Txs L_t.

Table 5.5 depicts the power loss caused with the increase in the number of PU-Txs. The power loss caused when number of PU-Tx are increased from 3 to 4 is 3dB, when number of PU-Txs increased from 4 to 5 is 1.75dB and when the number of PU-Txs are increased from 5 to 6 is 1dB.

Table 5.5 Average bit error rate values for CR-OC system obtained by varying L_t

Parameter	Number of PU-Txs L_t				Notes
	L_t=3	L_t=4	L_t=5	L_t=6	
Average bit error rate	0.09	0.14	0.18	0.20	Q_p=5dB, P_l=10dB, K_r=3, M_r=1
Power Loss (dB)	3	1.75	1		

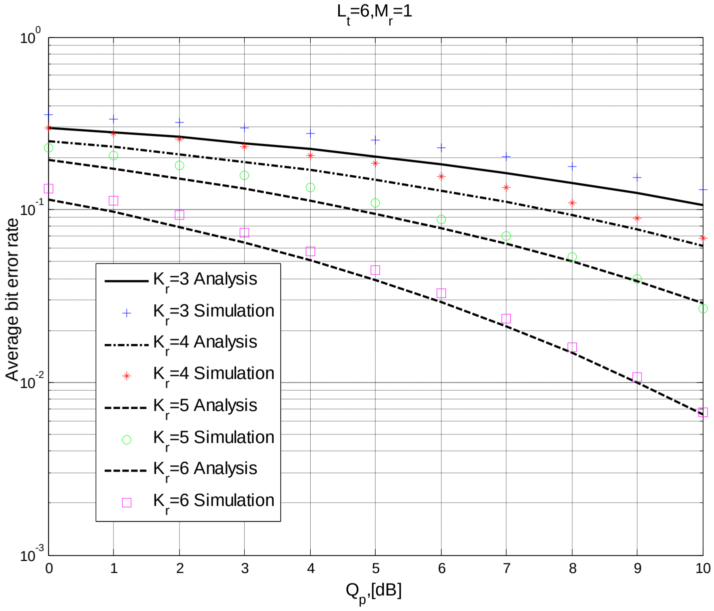

Fig. 5.6 Average BER of the CR-OC system versus Q_p for different number of SU-Rx receive antennas K_r.

The average BER of the CR-OC system for different number of receive antennas is shown in fig. 5.6. Increasing the number of antennas results in the BER performance improvement of the system. Employing OC also results in the power saving .When number of antennas are increased from 3 to 4 the power gain achieved is 2.5 dB, when increased from 4 to 5 is 3 dB and when number of antennas are increased from 5 to 6 is power gain is 3.5dB. The average bit error rate of the system falls with the increase in interference constraint Q_p.

Table 5.6 Average bit error rate values of CR-OC system obtained by varying K_r

Parameter	Number of SU-Rx antennas				Notes
	K_r=3	K_r=4	K_r=5	K_r=6	
Average bit error rate	0.20	0.15	0.09	0.04	Q_p=5dB, P_l=10dB, L_t=6, M_r=1
Power Saving(dB)	2.5		3	3.5	

5.1.4 Outage probability

The outage probability of the CR-OC system is shown in fig.5.7.The outage probability of the system for L_t=3, 4, 5, 6 is 0.83, 0.91, 0.93 and 0.95 at Q=5dB respectively.

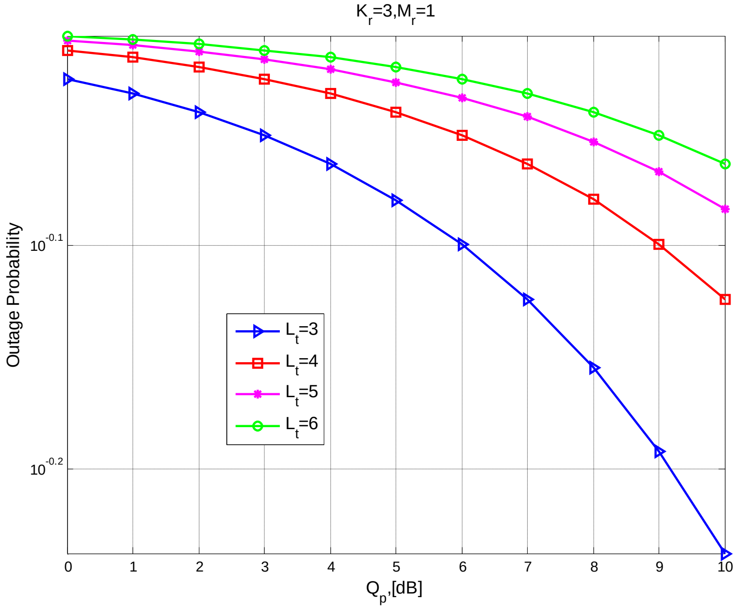

Fig. 5.7 Outage probability of the CR-OC system versus Q_p as a function of number of PU-Txs L_t.

The outage probability tends to decrease with the increase in interference power constraint. Therefore as the bound on the interference constraint becomes loose, the probability of the unsatisfactory reception over a given area is reduced. The outage probability of the CR-OC system with the varying number of SU-Rx antennas is shown in fig.5.8. It is observed that the outage probability of the system reduces with the increase in the number of SU-Rx antennas.

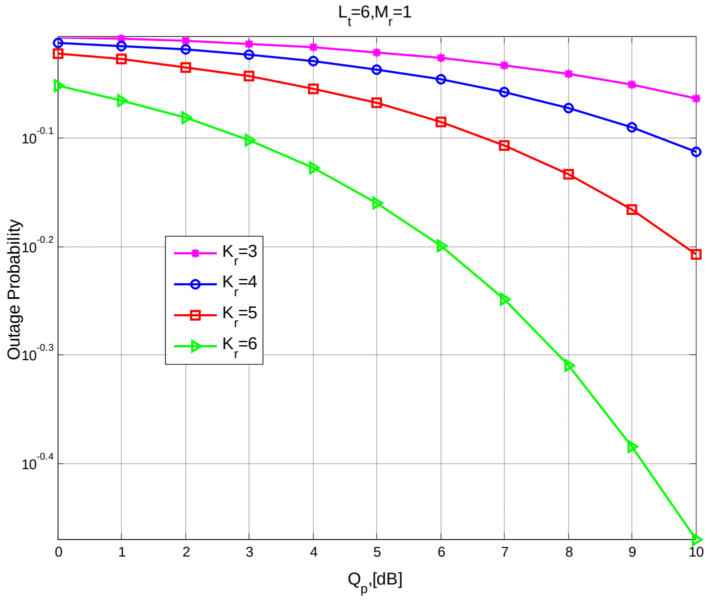

Fig. 5.8 Outage probability of the CR-OC system versus Q_p as a function of number SU-Rx antennas K_r.

5.2 CR-MRC

In this section analytical results of the average post processing SIR, ergodic capacity, outage probability and average BER of the CR-MRC system are presented for any arbitrary number of interferers. All the parameters taken are same as in CR-OC system. These results are utilized to compare the performance of CR-OC system with CR-MRC system. The results are obtained by varying both L_t and K_r.

5.2.1 Average Post Processing SIR

The approximated analysis results of the average post processing SIR for the CR-MRC system are given in fig. 5.9. From the figure, it is seen that the average post processing SIR of the system degrades with the increase in number of PU-Txs. However, the decrease in average post processing SIR becomes small for the further increase in the number of PU-Txs. The approximated analytical results for the average post processing SIR for different number of PU-Tx are given in table 5.7.

The average post processing SIR for L_t=3 is -5dB, for for L_t=4 is -6.25dB, for L_t=5 is -7.21dB and for L_t=6 is -8.01dB. The SIR loss for different number of interferers is evaluated in table

5.7. When number of PU-Txs is increased from 3 to 4, the loss in SIR is 1.25 dB, when antennas are increased from 4 to 5 is 0.9 dB and when number of PU-Tx is increased from 4 to 6, the SIR loss is 0.8 dB. Therefore, similar to OC, the SIR loss of the CR-MRC system decreases with the further increase in the number of interferers.

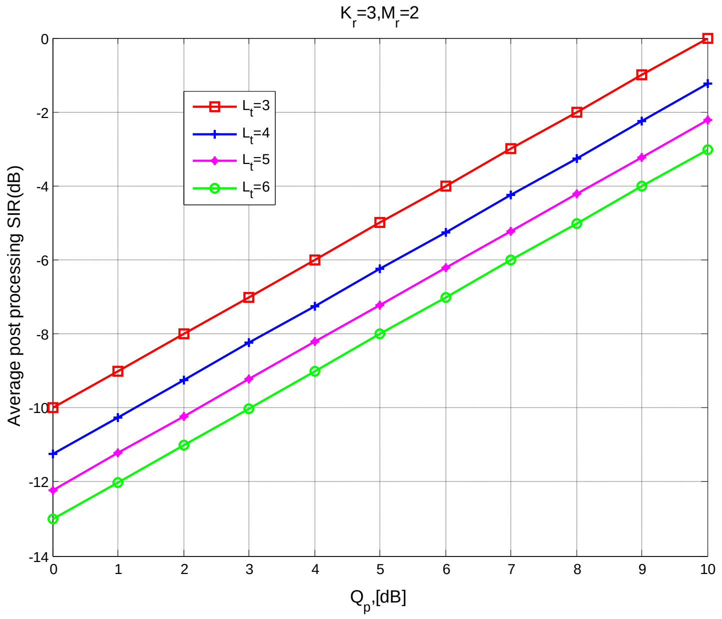

Fig. 5.9 Average post processing SIR of the CR-MRC system versus Q_p for different number of PU-Txs L_t.

Table 5.7 Average post processing SIR values of the CR-MRC by varying L_t

Parameter	Number of PU-Txs L_t				Notes
	L_t=3	L_t=4	L_t=5	L_t=6	
Average Post Processing SIR(dB)	-5	-6.25	-7.21	-8.01	Q_p=5dB, P_l=10dB, K_r=3, M_r=2
SIR Loss (dB)	1.25		0.96	0.8	

The average post processing SIR of the CR-MRC system for different numbers of SU-Rx receive antennas is shown in fig. 5.10. From figure, we know that the average post processing SIR increases with the increase in the number of SU-Rx antennas. Table 5.8 shows the results of the average post processing SIR for the different number of SU- Rx receive antennas. It also presents the gain achieved by increasing the number of SU-Rx receive antennas. The SIR gain achieved when number of SU-Rx antennas are increased from 3 to 4 is 1.25dB, when antennas are increased from 4 to 5, the gain is 0.96dB and gain is 0.8 dB when number of SU-Rx antennas are increased from 5 to 6.

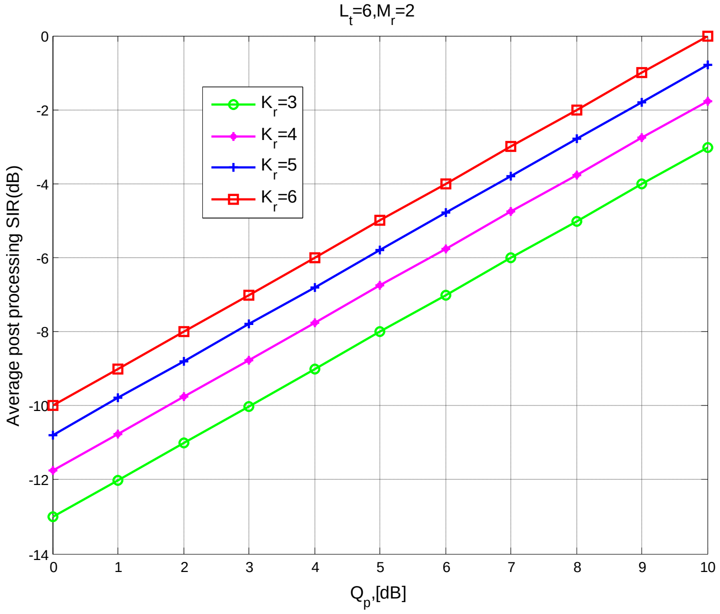

Fig. 5.10 Average post processing SIR of the CR-MRC system versus Q_p for different number of SU-Rx receive antennas K_r.

Table 5.8 Average post processing SIR values for CR-MRC system by varying K_r

Parameter	Number of SU-Rx antennas				Notes
	K_r=3	K_r=4	K_r=5	K_r=6	
Average post Processing SIR(dB)	-8.01	-6.76	-5.8	-5	Q_p=5dB, P_I=10dB, L_t=6, M_r=2
SIR gain(dB)	1.25	0.96	0.8		

5.2.2 Ergodic Capacity

The results of the ergodic capacity of the CR-MRC system for different number of PU-Txs are presented in fig.5.11.Similar to CR-OC, increasing the PU-Txs degrade the performance of the CR-MRC system. From the figure we can see that the decrease in ergodic capacity becomes small with the further increase in the number of PU-Txs. The ergodic capacity of the CR-MRC system for L_t=3, 4, 5 and 6 is 0.84, 0.70, 0.61 and 0.54 at Q=5dB, respectively. Table 5.9 shows the ergodic capacity loss caused when number of the number of PU-Txs are increased. From figure we observe that the increment in Q_p increases the ergodic capacity of CR-MRC in the same manner as in the case of CR-OC.

From table 5.9, we see that the decrease in the ergodic capacity when number of PU-Txs is increased from 3 to 4 is 15%, from 4 to 5 is 14% and when the number of PU-Tx is increased from 5 to 6 is 11%.

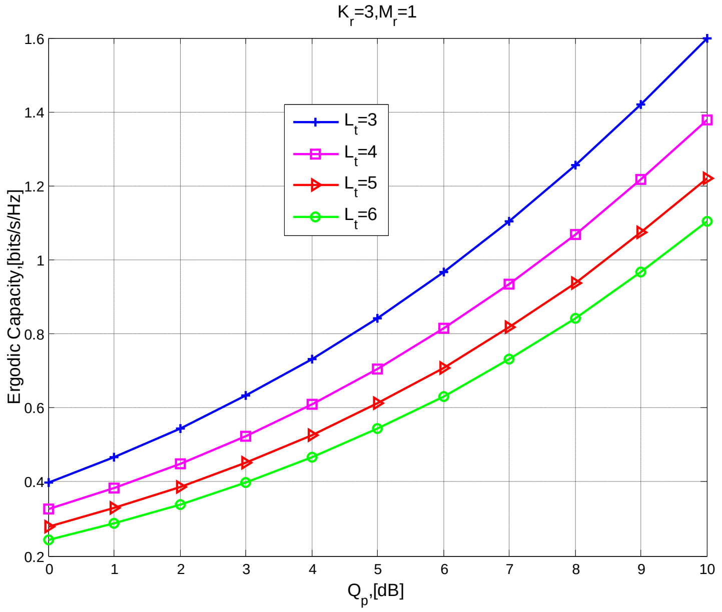

Fig. 5.11 Ergodic capacity of the CR-MRC versus Q_p for different number of PU-TXs L_t.

Table 5.9 Ergodic capacity values for CR-MRC system obtained by varying L_t

Parameter	Number of PU-Txs L_t				Notes
	L_t=3	L_t=4	L_t=5	L_t=6	
Ergodic Capacity (bits/s/Hz)	0.84	0.71	0.61	0.54	Q_p=5dB, P_l=10dB, K_r=3, M_r=1
Capacity Loss (%)	15%	14%	11%		

The ergodic capcity of the CR-OC system with different number of SU-Rx antennas is shown in fig 5.12. We observe that the capacity of the CR-MRC system tends to increase with the increase in the number of receive antennas. But with the further increase in the number of receive antennas the increase in the ergodic capacity become small.

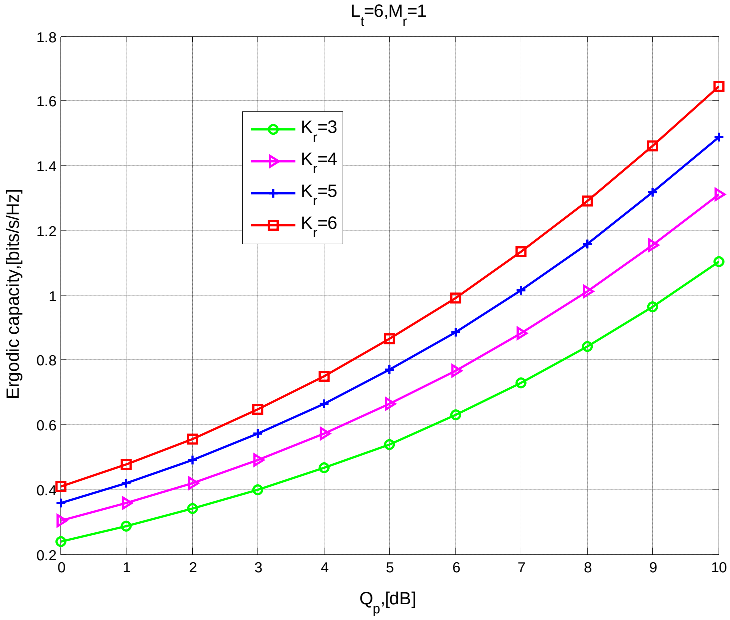

Fig. 5.12 Ergodic capacity of the CR-MRC versus Q_p for different number of SU-Rx antennas K_r.

Table 5.10 Ergodic capacity values for the CR-MRC system by varying K_r

Parameter	Number of SU-Rx antennas K_r				Notes
	K_r=3	K_r=4	K_r=5	L_t=6	
Ergodic Capacity (bits/s/Hz)	0.54	0.66	0.77	0.85	Q_p=5dB,P_I=10dB, K_r=3, M_r=1
Capacity Gain(%)	22%	17%	10%		

5.2.3 Average bit error rate

Fig. 5.13 shows the results of average BER for CR-MRC system. The average BER for CR-MRC at L_t=3, 4, 5 and 6 is 0.18, 0.20, 0.22 and 0.24 at Q_p=5dB, respectively.

From figure it is known that with the increase in the number of interferers, the BER of the system increases. However, this increase becomes very small with the further increase in the number of PU-Txs. The average BER of the system decreases with the increase in the interference constraint Q_p.

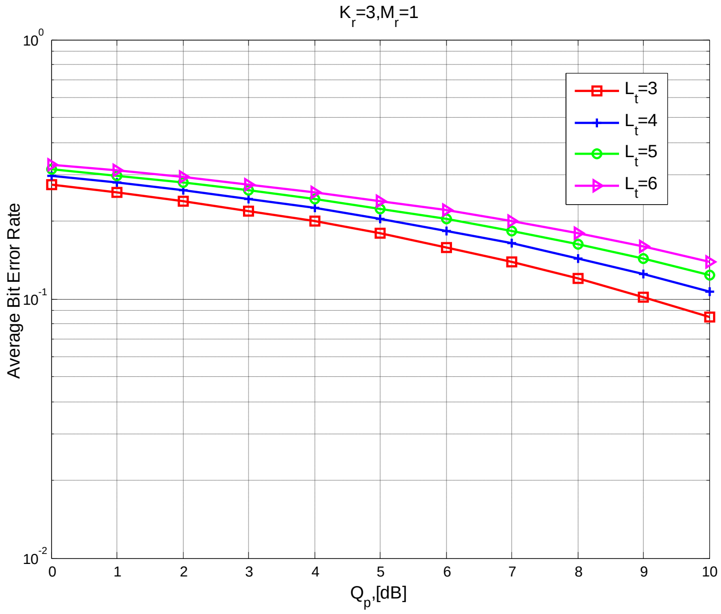

Fig. 5.13 Average BER of the CR-MRC versus Q_p for different number of PU-TXs L_t

Table 5.11 Average bit error rate values for CR-MRC system by varying L_t

Parameter	Number of PU-Txs L_t				Notes
	L_t=3	L_t=4	L_t=5	L_t=6	
Average BER	0.18	0.20	0.22	0.24	Q_p=5dB,P_l=10dB, K_r=3, M_r=1
Power Loss (dB)	1	1	1		

From table we see that when number of interferes are increased by 1, the power required increases by 1dB.

Fig. 5.14 shows the average BER of the CR-MRC system as a function of Q_p for the varying number of antennas at SU-Rx. With the increase in the number of SU-Rx antennas, there is a corresponding decrease in the average BER of the system. The average BER for CR-MRC at K_r=3, 4, 5 and 6 is 0.24, 0.21, 0.19 and 0.17at Q_p=5dB, respectively. But from figure we can see that the decrease in the BER with the increase in number of antennas become small when the number of antennas are further increased i.e when number of antennas are increased from 3 to 4, the power saving is 1.5dB, from 4 to 5 is 1dB, and when number of receive antennas are increased from 5 to 6, the power gain is also 1dB.

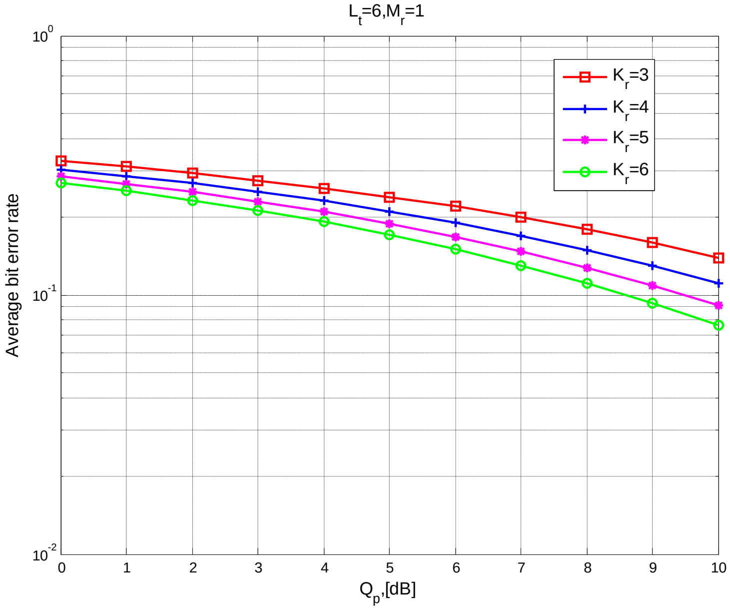

Fig. 5.14 Average BER of the CR-MRC system versus Q_p for different number of PU-Txs L_t.

Table 5.12 Average bit error rate values of the CR-MRC system by varying K_r

Parameter	Number of SU-Rx antennas K_r				Notes
	K_r=3	K_r=4	K_r=5	K_r=6	
Average BER	0.24	0.21	0.19	0.17	Q_p=5dB,P_l=10dB, K_r=3, M_r=1
Power gain(dB)	1.5	1	1		

5.2.4 Outage Probability

The outage probability of the CR-MRC system versus the number of PU-Txs is shown in fig. 5.15.The outage probability of the CR-MRC system increases with the increase in number of PU-Txs as is the case with CR-MRC. With the further increase in the number of PU-Txs, the increment in outage probability becomes small. The outage probability of CR-MRC system falls with the increase in interference power constraint.

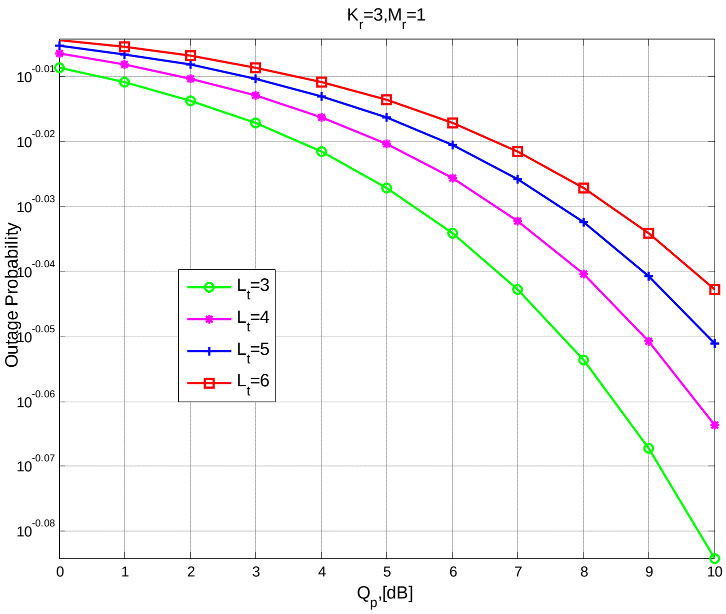

Fig. 5.15 Outage probability of the CR-MRC system versus Q_p for different number of PU-Txs L_t.

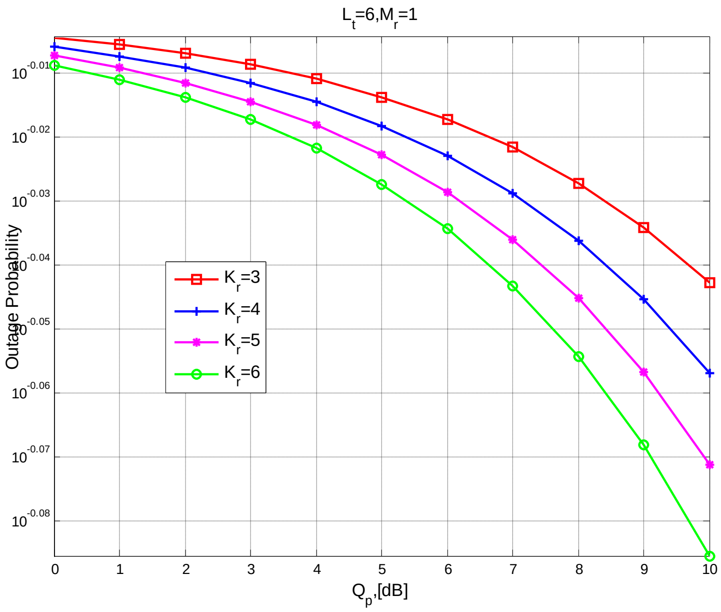

Fig. 5.16 Outage probability of the CR-MRC system versus Q_p for different number of SU-Rx antennas K_r.

The outage probability of the CR-OC system versus the number of SU-Rx antennas is shown in fig.5.16. The outage probability of the CR-MRC system decreases with the increase in number of SU-Rx antennas as is the case with CR-OC. It is concluded that with the further increase in the number of SU-Rx antennas, the decrease in outage probability become small.

5.3 Comparison of CR-OC and CR-MRC System

This section presents the comparison of the CR-OC and CR-MRC system in terms of average post processing SIR, ergodic capacity, average BER and outage probability. These results are obtained by varying the number of PU-Txs and SU-Rx receive antennas. The comparison of CR-OC and CR-MRC in terms of number of PU-Txs is presented in fig 5.17.

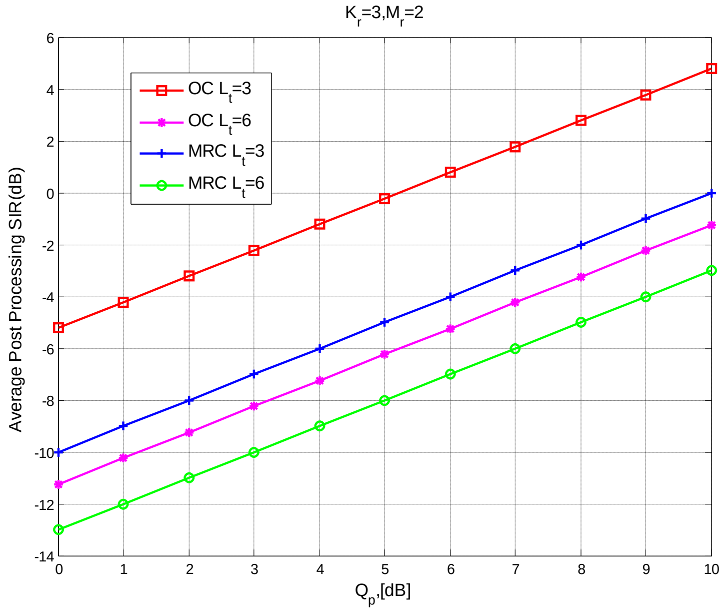

Fig.5.17 Average post processing SIR comparison between CR-OC and CR-MRC with L_t as parameter

Figure shows that the SIR gain achieved in CR-OC is very large in comparison to CR-MRC for L_t=3, but for L_t=6 the SIR gain of CR-OC over CR-MRC becomes small. The comparison of average post processing SIR in terms of K_r is presented in fig 5.18. Figure shows that with the increase in number of antennas at SU-Rx, the SIR gain of CR-OC system over CR-MRC system increases.

The ergodic capacity of CR-OC and CR-MRC system for L_t=3 and L_t=6 is compared in fig 5.19.Results indicate that significant capacity gains can be achieved in case of CR-OC as compared to CR-MRC system. It is concluded that when number of PU-Txs and SU-Rx antennas are equal i.e L_t=K_r=3, the performance of CR-OC system outperforms CR-MRC. Whereas for L_t=6 and K_r=3, i.e the number of PU-Tx causing interferers are more than the number of SU-Rx antennas, the performance improvement of CR-OC over CR-MRC becomes small but still OC performs better than MRC.

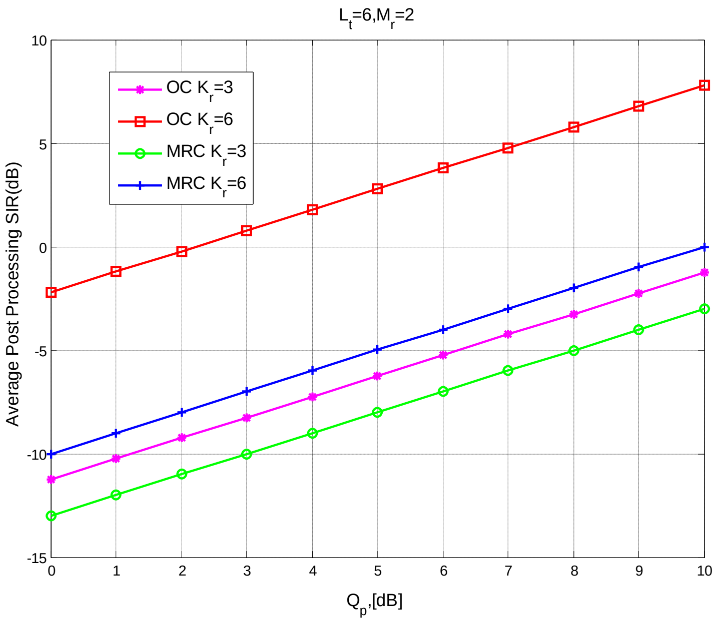

Fig.5.18 Average post processing SIR comparison between CR-OC and CR-MRC with K_r as parameter

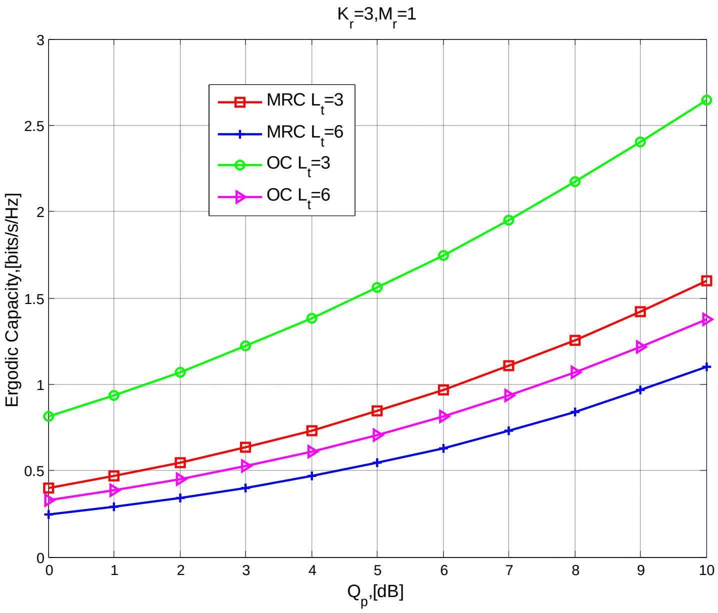

Fig.5.19 Ergodic capacity comparison between CR-OC and CR-MRC with L_t as parameter

The comparison of ergodic capacity CR-OC and CR-MRC system with K_r as parameter is presented in fig 5.20. The CR-OC system gives better performance as compared to CR-MRC system. It is concluded that with the increase in the number of SU-Rx antennas, a noticeable improvement is obtained with CR-OC system.

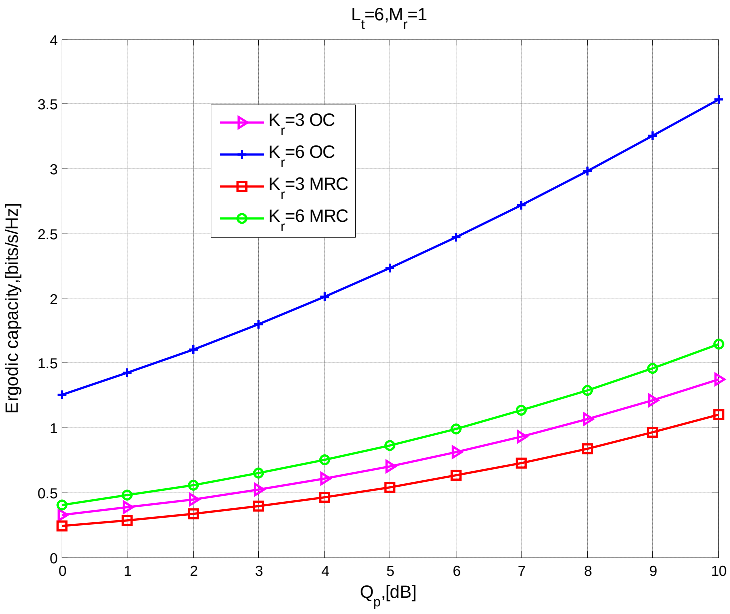

Fig. 5.20 Performance comparison of ergodic capacity between CR-OC and CR-MRC with K_r as parameter

Fig. 5.21 compares the average BER of CR-OC and CR-MRC systems for L_t=3 and L_t=6. It is observed that improved average BER is obtained in case of CR-OC as compared to CR-MRC. Significant improvement is observed between CR-OC and CR-MRC for L_t=K_r=3, whereas for L_t=6 and K_r=3, a smaller improvement is observed.

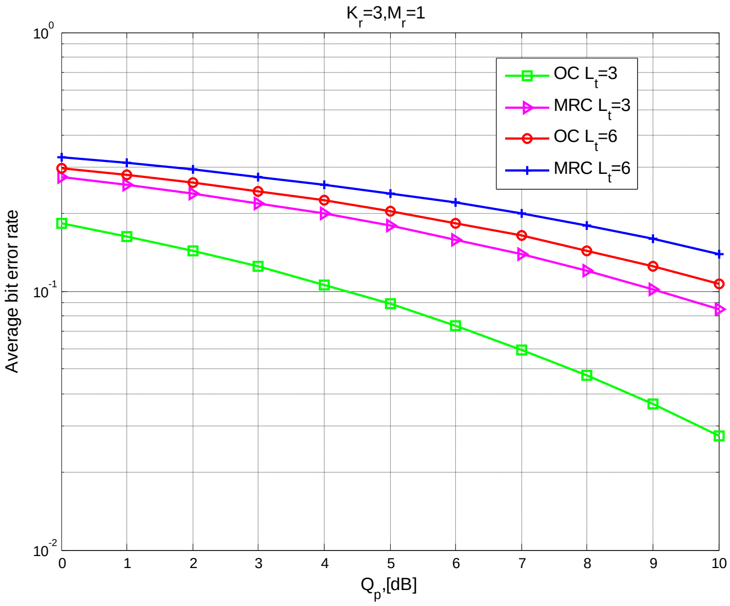

Fig. 5.21 Performance comparison of ergodic capacity between CR-OC and CR-MRC with L_t as parameter

Thus, it is concluded that CR-OC system performs better than CR-MRC system even with the increased number of interferers.

The average BER of the CR-OC system with K_r as parameter is shown in fig.5.22.The BER performance of the CR-OC system is better than CR-MRC system. The improvement in average BER becomes significant with the increase in the number of SU-Rx antennas.

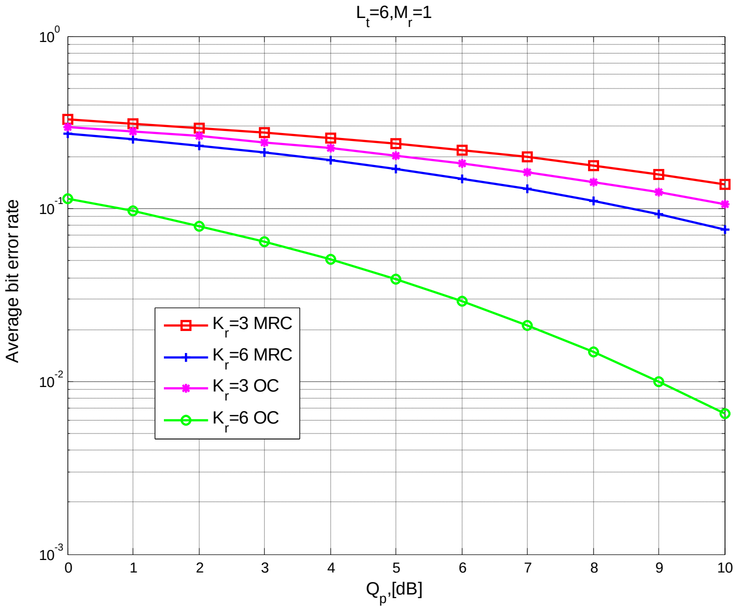

Fig. 5.22 Performance comparison of average BER between CR-OC and CR-MRC with K_r as parameter

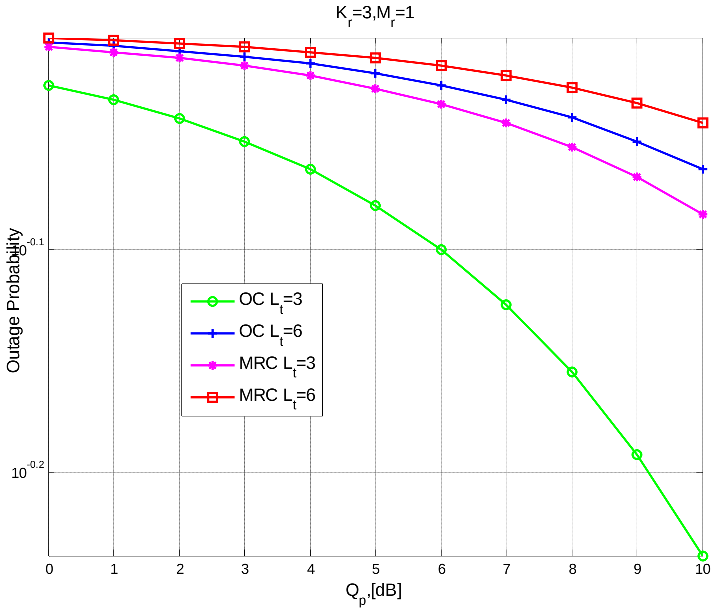

Fig. 5.23 Performance comparison of outage probability between CR-OC and CR-MRC with L_t as parameter

The comparison of outage probability of both systems with L_t as parameter is presented in fig. 5.23. As in the case of average BER, the outage probability of the CR-OC system is less than CR-MRC system but this performance improvement is more noticeable for L_t=3.For L_t=6,the improvement of CR-OC system over CR-MRC system becomes small.

The comparison of outage probability for both systems with K_r as parameter is shown in fig. 5.24. Similar to BER, the outage probability decreases with the increase in number of SU-Rx receive antennas. The improvement outage probability becomes even more noticeable when the number of SU-Rx antennas is further increased.

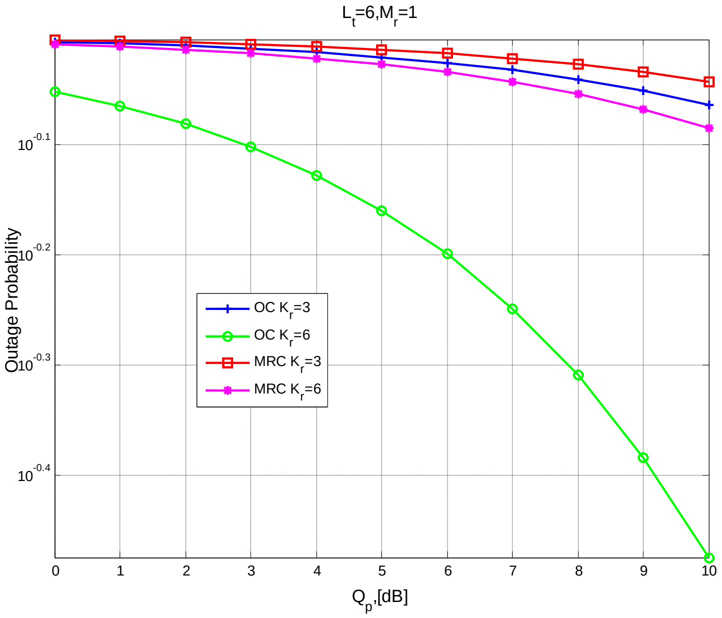

Fig. 5.24 Performance comparison of outage probability between CR-OC and CR-MRC with K_r as parameter

Table 5.13 shows performance analysis of the average post processing SIR, ergodic capacity, average BER and outage probability for the CR-OC and CR-MRC system. The SIR gain of CR-OC over CR-MRC for L_t=3, 4, 5 and 6 is 4.8dB, 3.02 dB, 2.21dB and 1.78 dB at Q_p=5dB, respectively. It is shown that for L_t=3, 4, 5 and 6 at Q_p=5dB, the ergodic capacity gain of CR-OC is higher than CR-MRC by about 86%, 51%, 38% and 31%, respectively. The average post processing SIR of CR-MRC for L_t=3 is -5dB, whereas the same SIR is achieved in case of CR-OC for L_t=5.The ergodic capacity 0.84 bits/s/Hz is obtained in CR-MRC for L_t=3 , whereas the same ergodic capacity is achieved in case of CR-OC for L_t=5.Similarly, the average BER of CR-MRC for L_t=3 is 0.18 and same average BER is obtained for L_t=5 in case of CR-MRC.

Also the outage probability for L_t=6 is 0.95 in CR-OC system and the same outage probability is obtained in CR-MRC for L_t=4. Thus, it is concluded that CR-OC with two more interferers gives the same performance as CR-MRC.

Table 5.13 Comparison of CR-OC system with CR-MRC system

Parameters	Number of PU-Txs L_t								Notes
	L_t=3		L_t=4		L_t=5		L_t=6		
	CR-OC	CR-MRC	CR-OC	CR-MRC	CR-OC	CR-MRC	CR-OC	CR-MRC	
Average Post Processing SIR(dB)	-0.23	-5	-3.23	-6.25	-5	-7.21	-6.25	-8.01	
Ergodic capacity(bits/s/Hz)	1.56	0.84	1.07	0.71	0.84	0.61	0.71	0.54	Q_p=5dB, P=10dB, K_r=3,γ_0=5
Average bit error rate	0.09	0.18	0.14	0.20	0.18	0.22	0.20	0.24	
Outage Probability	0.83	0.94	0.91	0.95	0.93	0.96	0.95	0.97	
SIR Gain(dB)	4.8		3.02		2.21		1.76		
$\frac{C_{CR-OC}}{C_{CR-MRC}}$	86%		51%		38%		31%		

In order to achieve average BER of 10^{-1} at L_t=3 for both the proposed systems, CR-OC requires 5dB less power as compared to CR-MRC. In addition, with L_t=6, for an average BER of $10^{-0.9}$, OC leads to a power saving of nearly 1.5dB over MRC. Thus, it is concluded that the CR-OC system gives better performance than CR-MRC even when number of interfering signals are greater than the number of SU-Rx antennas.

Chapter 6

CONCLUSION AND FUTURE SCOPE

6.1 Conclusion

Cognitive radio provides efficient spectrum utilization without causing any interference to already existing users. In underlay cognitive radio SU shares the same spectrum with PU. To protect the PU from harmful interference, the transmit power of the SU follows the interference constraint set at PU-Rx. Due to this interference constraint the capacity of spectrum sharing system becomes low. However, the capacity of the SU can be improved by employing diversity techniques at the SU-Rx. The performance of the SU is also affected by the interference from the PU-Tx. Therefore OC is employed at SU-Rx to remove the interference generated by PU-Txs. OC is optimum from the standpoint of increasing the SIR at the combiner output. It is concluded that OC reduces the interference at SU-Rx and acceptable performance is achieved even if the number of PU-Txs is further increased. The performance of CR-OC system is compared with CR-MRC system. It is concluded that the OC achieves better performance in comparison to MRC even if the number of PU-Txs are greater than the number of SU-Rx antennas. Results show that CR-OC system with two more interferers gives the same performance as CR-MRC. Also we have seen that the CR-OC system leads to much power consumption as compared to CR-MRC.

6.2 Future Scope

The presented work can be extended to MIMO-CR systems where TAS scheme can be used at the SU-Tx to select the best transmitting antenna. This system can be further extended to the scheduling MIMO-CR in which the user with maximum average post processing SNR is selected.

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