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Improving Ergodic and Outage Capacity of Spectrum Sharing Cognitive Radio Networks

[1]Neha Singh, [2]Balaji. Gawalwad
[1]Dept. of E&TC, SVIT,Pune University, Nashik, Maharashtra, India
[2]H.O.D,Dept of E&TC, SVIT, Nashik, Maharashta, India

Abstract-Cognitive Radio technology helps in designing wireless system for efficient deployment of radio spectrum with its sensing technique,self adaptation and spectrum sharing. Spectrum sharing is an effective method of alleviating the scarcity of radio spectrum problem by allowing unlicensed users (secondary users) to coexist with licensed users (primary users) under the condition of protecting the later from harmful interference. This dissertation work emphasizes on the throughput maximization of spectrum sharing cognitive radio networks. It proposes an innovative spectrum sharing technique that will significantly improve achievable throughput of the network. This work introduces novel receiver and a frame structure for spectrum sharing. The problem of optimal power allocation that maximizes the ergodic capacity of the system under average transmits and interference power constraints are also studied.This work also includes maximization of outage capacity under TIFR transmission policy and proposed spectrum sharing methodology.

Keywords-Cognitive radio, Ergodic capacity, Outage capacity,Optimal power allocation, Spectrum sensing, Spectrum sharing, Throughput maximization.

I. INTRODUCTION

According to recent measurements by the federal communications commission (FCC), the current fixed spectrum allocation policy have resulted in several bands being severely underutilized both in temporal and spatial manner [4]. Hence the need for more available spectrum to develop better wireless services becomes increasingly pressing. Cognitive radio [7] is considered to be one of the most promising solutions to alleviate the spectrum scarcity problem and support the increasing demand for wireless communications by allowing unlicensed users to access licensed frequency bands, under the condition of protection the quality of service (QOS) of the licensed networks. This realization by the FCC of the inefficient use of the spectrum under the current fixed spectrum allocation policy led to the decision to allow access of unlicensed users to the broadcast television spectrum at locations where that spectrum is not being used by licensed services.

II. RELATED WORK

Two main approaches have been developed for cognitive radio so far, regarding the way of secondary user accesses the licensed spectrum :

i. Through opportunistic spectrum access (OSA), also known as interweave scheme, according to which when frequency band is detected not being used by the primary users than it is accessed by a secondary user [9], and
ii. Through spectrum sharing (SS), also known as underlay scheme, according to which under the condition of protecting primary users from harmful interference secondary users coexist with them [1],[12].

Recently, in order to increase the throughput of the two afore mentioned schemes , a third hybrid approach was proposed, in which the secondary users sense for the status (active/idle) initially, of a frequency band (as in the OSA) and adapt their transmit power based on the decision made by spectrum sensing, to avoid causing harmful interference (as in SS) [11]. The frame structure of thus approach is same as in OSA and consists of a sensing slot and a data transmission slot.
A secondary user that employs this frame structure ceases data transmission at the beginning of each frame, perform spectrum sensing forτ units of time, in order to determine the status (active/idle) of the frequency band, and uses the remaining frame duration T-τ for data transmission. Therefore, an inherent tradeoff exists in this hybrid approach between the duration of spectrum sensing and data transmission. This tradeoff is studied in [11] and [8] for the ergodic throughput of cognitive radio networks and is similar to the one seen in OSA cognitive radio networks [10].

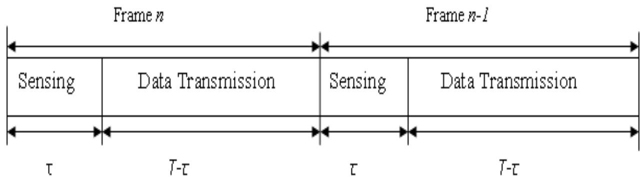

Fig.1 Frame structure of conventional sensing-based spectrum sharing

The sensing-throughput tradeoff problem becomes very significant when the hybrid approach is used to increase the throughput of spectrum sharing cognitive radio networks, since the primary signals under detection are very weak and may therefore lead to very high sensing times that would have a detrimental effect on their achievable throughput. In addition, this frame structure disrupts the continuity of communication in spectrum sharing cognitive radio networks and results in a decrease of their throughput by a factor of $(T-\tau)/T$ when the primary users are active.

III. PROPOSED SPECTRUMSENSING SCHEME

A. System Overview

In the beginning,an initial spectrum sensing is performed to determine the status of the frequency band. Based on the decision of spectrum sensing, the secondary user communicate using higher transmit power i.e. P0 if the primary users are detected to be idle and lower power i.e. P1 otherwise.

In the following, the secondary receiver decodes the signal sent by the secondary transmitter, strips it away from the received signal and uses the remaining signal to perform spectrum sensing, in order to determine the action of the cognitive radio system in the next frame.at the end of the frame, if the status of the primary users has changed after the initial spectrum sensing was performed, the secondary users will change their transmit power from higher to lower or vice versa, based on the spectrum sensing decision (which is sent back to the transmitter via a control channel), in order to avoid causing harmful interference to the primary users. Finally, the process is repeated.

B. Receiver Structure

The receiver structure of the proposed cognitive radio system is presented in Fig 3. The received signal at the secondary receiver is given by

$$y = \Theta x_p + x_s + n \quad (1)$$

where Θdenotes the actual status of the frequency band (Θ=1 if the frequency band is active, where asΘ=0 if the frequency band is idle), x_p and x_s represent the received signal from the primary users and the secondary transmitter, respectively. Finally, n denotes the additive noise. The received signal y is initially passed through the decoder, as depicted in Fig. 3. Where the signal from the secondary transmitter is obtained.

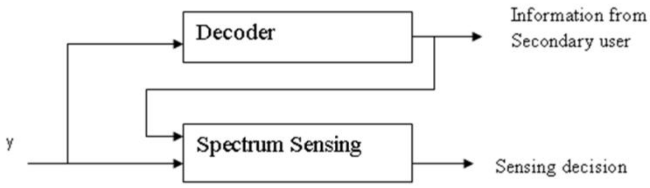

Fig. 3 Receiver structure of the proposed cognitive radio system

In the following, the signal from the secondary transmitter is cancelled out from the aggregate received signal y and the remaining signal

$$\bar{y} = \Theta x_p + n \quad (2)$$

is used to perform spectrum sensing. As a result, instead of using a limited amount of time τ (as in the frame structure of Fig. 2), almost the whole duration of the frame T can be used for spectrum sensing under the proposed cognitive radio system. This way, we are able to perform spectrum sensing and data transmission at the same time and therefore maximize the duration of both.

C. Frame Structure

The frame structure of the proposed cognitive radio system is presented in Fig. 4 and consists of a single slot during which both spectrum sensing and data transmission are performed at the same time using the receiver structure presented in the previous subsection. The advantage of the proposed frame structure is that the spectrum sensing and data transmission times are simultaneously maximized.

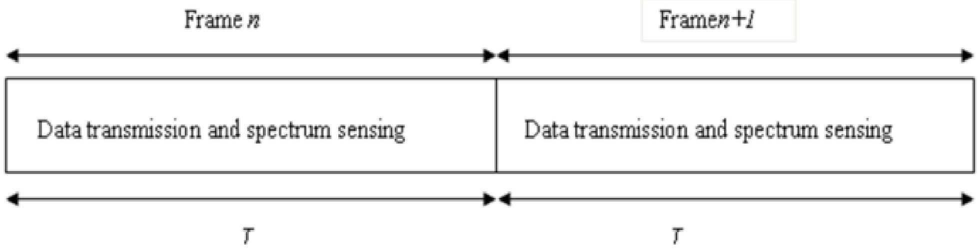

Fig. 4 Frame structure of the proposed cognitive radio system

The significance of this result is twofold. First, under perfect cancellation, the increased sensing time:

- Enables the detection of very weak signals from the primary users, the detection of which under the frame structure of Fig. 4 would significantly reduce the data transmission time, hence the throughput of the cognitive radio system.

- Leads to an improved detection probability, thus better protection of primary users from harmful interference, and a decreased false alarm probability, which enables a better use of the available unused spectrum, considering the fact that a false alarm prevents the secondary user from accessing an idle frequency band using higher transmit power, and therefore limits their achievable throughput.
- Facilitates the use of more complex spectrum sensing techniques that exhibit increased spectrum sensing capabilities, but requires higher sensing time (such as Cyclostationary detection, Generalised Likelihood Ratio Test (GLRT)- based or covariance-based spectrum sensing techniques), which prohibits their application for quick periodical spectrum sensing under the frame structure of Fig. 4.
- The calculation of the optimal sensing time is no longer an issue and does not require to be adapted or transmitted back to the secondary users;
- Continuous spectrum sensing can be achieved under the proposed cognitive radio system, which ensures better protection of the primary networks.

Finally, the second important aspect is that the sensing time slot τ of the frame structure of Fig. 4 is now used for data transmission, which leads to an increase in the achievable throughput of the cognitive radio system on the one hand, and facilitates the continuity of the data transmission on the other.

IV. NETWORK MODEL

In the cognitive radio system presented in Fig. 5 that operates based on the proposed spectrum sharing scheme that is described in the following. Let g and h denote the instantaneous channel power gains from the secondary transmitter (SU-Tx) and the primary receiver (PU-Rx), respectively. The channel g and h are assumed to be ergodic, stationary and known at the secondary users with probability density function (pdf) $f_g(g)$ and $f_h(h)$, respectively, whereas the noise is assumed to be circularly symmetric complex guassian (CSCG) with mean zero and variance σ_n^2 namely CN(0,σ_n^2) that in practice, it might be difficult to obtain perfect information of the channel h for fast fading channels. In the following, it is described how the proposed spectrum sharing scheme operates and present the receiver and frame structure employed in this cognitive radio system. In practice, the channel power gain h can be obtained via, e.g., estimating the received signal power from the PU-Rx when it transmits, under the assumptions of the pre-knowledge on the PU-Rx transmit power level and the channel reciprocity.

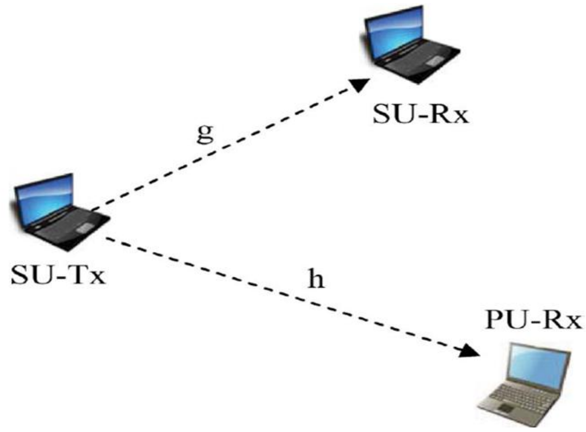

Fig. 5 Proposed network model

V. ANALYTICAL DESCRIPTION

A. *Ergodic Capacity*

In this section, the problem of deriving the optimal power allocation strategy that maximizes the ergodic capacity of the cognitive radio network that operates under the proposed spectrum sharing scheme is discussed. In the proposed cognitive radio system, the secondary users adapt their transmit power at the end of each frame based on the decision of spectrum sensing, and transmit using higher power P_0 when the frequency band is detected to be idle and lower power $P_1$when it is detected to be active. Following the approach of [1], [2], [13], the instantaneous transmission rates when thefrequency band is idle (H0) and active (H1) are given by

$$r_0 = \log_2\left(1 + \frac{gp_0}{\sigma_n^2}\right)$$

$$r_1 = \log_2\left(1 + \frac{gp_1}{\sigma_n^2 + \sigma_p^2}\right)$$

respectively, where σ_p^2 denotes the received power from the primary users. The latter parameter restricts the achievable throughput of all spectrum sharing cognitive radio networks and indicates the importance of spectrum sensing and optimal power allocation on the throughput maximization of spectrum sharing cognitive radio networks.

However, the perfect spectrum sensing may not be achievable in practice, where the actual status of the primary users might be falsely detected. Therefore, the four different cases of instantaneous transmission rates based on the actual status of the primary users (active/idle) and the decision of the secondary users (primary users present/absent) as follows:

$$r_{00} = \log_2\left(1 + \frac{gp_0}{\sigma_n^2}\right) \quad (3)$$

$$r_{01} = \log_2\left(1 + \frac{gp_1}{\sigma_n^2}\right) \quad (4)$$

$$r_{10} = \log_2\left(1 + \frac{gp_0}{\sigma_n^2 + \sigma_p^2}\right) \quad (5)$$

$$r_{11} = \log_2\left(1 + \frac{gp_1}{\sigma_n^2 + \sigma_p^2}\right) \quad (6)$$

Here, the first index number of the instantaneous transmission rates indicates the actual status of the primary users ("0" for idle, "1" for active) and the second index number, the decision made by the secondary users ("0" for absent, "1" for present). In order to keep the long term power budget and effectively protect the primary users from harmful interference, consider an average (over all fading states) transmit and interference power constraint that can be formulated as follows :

$$E_{g,h}\{P(H_0)(1 - P_{fa})P_0 + P(H_0)P_{fa}P_1 + P(H_1)(1 - P_d)P_0 + P(H_1)P_dP_1\} \leq P_{av} \quad (7)$$

$$E_{g,h}\{P(H_1)(1 - P_d)hP_0 + P(H_1)P_dhP_1\} \leq \Gamma \quad (8)$$

Where $P(H_0)$ and $P(H_1)$ denote the probability that the frequency band is idle and active, respectively, P_d and P_{fa} represent the detection and false alarm probability, respectively, whereas P_{av} denotes the maximum average transmit power of the secondary users, and Γ the maximum average interference power that is tolerable primary users. The reason for choosing an average interference power constraint is based on the results in [14] and [11], which indicate that an average interference power constraints leads to higher ergodic throughput for the cognitive radio system, and provides better protection for the primary users compared to a peak interference power constraint.

Finally, the optimization problem that maximizes the ergodic throughput of the proposed spectrum sharing cognitive radio system under joint average transmit and interference power constraints can be formulated as follows:

$$C = E_{g,h}\{P(H_1)P_dr_{11} + P(H_0)P_{fa}r_{01} + P(H_1)(1 - P_d)r_{10} + P(H_0)(1 - P_{fa})r_{00}\} \quad (9)$$

B. Outage capacity of proposed spectrum sharing scheme

The ergodic capacity is used for fast fading channels or delay-insensitive applications [11], whereas for slow fading channels or delay-sensitive applications, such as voice and video transmission, the outage capacity [11], [12] comprises a more appropriate metric for the capacity of the system.The outage capacity Cout is defined as the highest transmission rate that can be achieved by the communications system with the probability of outage under a maximum value. In this section the outage capacity of the proposed spectrum sharing cognitive radio system is studied and the power allocation strategy for a combination of different constraint on the outage capacity is derived that include average transmit power constraints, average interference power constraints and peak interference power constraints. For power allocation the truncated channel inversion with fixed rate (TIFR) technique is considered, where the secondary transmitter uses the channel side information (CSI) to invert the channel fading, in order to achieve a constant signal-to-noise ratio (SNR) at the secondary receiver during the periods when the channels fade above a certain "cutoff" value. This adaptive transmission scheme offers the advantage of non-zero achievable rates for a target outage probability Pout = $\overline{(\text{Pout})}$, even when the fading is extremely severe such as in Rayleigh fading cases, where a constant transmission rate cannot be achieved under all fading states of the channel.

i. Outage capacity under average transmit and interference power constraints

These can be formulated as follows:

$$E_{g,h}\{P(H_0)(1 - P_{fa})P_0 + P(H_0)P_{fa}P_1 + P(H_1)(1 - P_d)P_0 + P(H_1)P_dP_1\} \leq P_{av} \quad (19)$$

$$E_{g,h}\{P(H_1)(1 - P_d)hP_0 + P(H_1)P_dhP_1\} \leq \Gamma \quad (20)$$

As mentioned in the beginning of this section, in the TIFR technique the secondary transmitter inverts the channel fading, in order to achieve a constant rate at the secondary receiver when the channel fading is higher than a "cutoff" threshold. We define here this cutoff threshold by γ0 when the primary users are detected to be idle and by γ1 when the primary users are detected to be active. The transmit power in both cases is suspended when the link g between the secondary transmitter and the respective receiver is weak compared to the interference channel h from the secondary transmitter to the primary receiver. Considering here the same metric, i.e. h/g, for the case that the primary users are detected to be idle, namely for P0(g, h) so that to effectively protect the primary users from harmful interference when a miss-detection occurs.

Therefore, the channel capacity under the TIFR policy can be obtained as follows:

$$C_{TIFR} = \max(\gamma_0, \gamma_1)\left\{\log\left(1 + \frac{1}{\sigma_2}\min\{t_1(\gamma_0, \gamma_1), t_2(\gamma_0, \gamma_1)\}\right)\left(1 - \frac{K_0\sigma^2}{\gamma_0 + \sigma^2} - \frac{K_1\sigma^2}{\gamma_1 + \sigma^2}\right)\right\} \quad (21)$$

where the maximum can be obtained by searching numerically for the optimal value of γ_0 and γ_1.

Finally the outage capacity of the proposed spectrum sharing cognitive radio network under joint average transmit and interference power constraints is given by,

$$C_{out} = max(\gamma_0)\left\{\log(1 + \frac{1}{\sigma^2}\min\{\overline{t_1}(\gamma_0), \overline{t_2}(\gamma_0)\}) \cdot (1 - \overline{P_{out}})\right\} \quad (22)$$

where the maximum can be obtained by searching numerically for the optimal value of γ_0.

ii. Outage capacity under both average and peakinterference power constraints

The aforementioned constraints can be formulated asfollows:

$E_{g,h}\{P(H_1)(1-P_d)hP_0(g,h)+P(H_1)P_d hP_1(g,h)\} \le \Gamma$ (23)

$P(H_1)(1-P_d)P_0(g,h)h \le Q_{peak}$ (24)

$P(H_1)P_d P_1(g,h)h \le Q_{peak}$ (25)

where we have considered the interference caused under both cases, namely when the frequency band is correctly detected to be active and falsely detected to be idle.

Therefore, the maximum capacity under the TIFR transmission policy can be obtained as follows:

$$C_{TIFR} = \max(\gamma_0,\gamma_1)\left\{\log\left(1+\frac{min\{q_1(\gamma_0,\gamma_1),q_2(\gamma_0),q_3(\gamma_1)\}}{\sigma^2}\right)\cdot\left(1-\frac{K_0\sigma^2}{\gamma_0+\sigma^2}-\frac{K_1\sigma^2}{\gamma_1+\sigma^2}\right)\right\} \quad (26)$$

where the maximum can be obtained by searching numerically for the optimal value of γ0 and γ1. Therefore the outage capacity is given by

$$C_{out} = max(\gamma_0)\left\{\log\left(1+\frac{min\{q_1(\gamma_0),q_2(\gamma_0),q_3(\gamma_0)\}}{\sigma^2}\right)\cdot(1-\overline{P_{out}})\right\} \quad (27)$$

where the maximum can be obtained by searching numerically for the optimal value of γ0.

iii. Outage capacity under average transmit and interference power constraints with high target detection probability

Now consider the case that a high target detection probability Pdis employed on the proposed spectrum sharing cognitive radio system, and that when the primary users are detected to be idle, the secondary transmitter accesses the frequency band in an opportunistic spectrum access manner, namely it does not impose an interference power constraint. In this case, the average transmits and interference power constraint take the following form:

$E_{(g,h)}\{\overline{K_0}P_0+\overline{K_1}P_1\} \le P_{av}$ (28)

$E_{(g,h)}\{P(H_1)\overline{P_d}hP_1\} \le \Gamma$ (29)

The transmit power P0 (when the primary users are detected to be idle) depends only on the channel g between the secondary transmitter and the respective receiver, and is independent of the interference channel h to the primary receiver.

As a result, the maximum capacity under the TIFR transmission policy is given by

$$C_{TIFR} = \max(\gamma_0,\gamma_1)\left\{\log\left(1+\frac{min\{u_1(\gamma_1),u_2(\gamma_0,\gamma_1)\}}{\sigma_2}\right)\cdot\left(1-\overline{K_0}+\overline{k_0}\exp\left(\frac{\gamma_0}{\sigma^2}\right)-\frac{\overline{K_1}\sigma^2}{\gamma_1+\sigma^2}\right)\right\} \quad (30)$$

where the maximum can be obtained by searching numerically for the optimal value of γ0 and γ1.

For a target outage probability the outage capacity is finally given by:

$$C_{out} = max(\gamma_0)\left\{\log(1+\frac{min\{\overline{u_1}(\gamma_0),\overline{u_2}(\gamma_0)\}}{\sigma^2})\cdot(1-\overline{P_{out}})\right\} \quad (31)$$

where the maximum can be obtained by searching numerically for the optimal value of γ0.

iv. Outage capacity under both average and peak interference power constraints with high target detection probability

In this last subsection, consider a similar scenario to one in the previous subsection, only this time under joint average and peak interference power constraints on the secondary transmitter. The aforementioned constraints can be expressed as follows:

$E_{(g,h)}\{P(H_1)\overline{P_d}hP_1(g,h)\} \le \Gamma$ (32)

$P(H_1)\overline{P_d}P_1(g,h)h \le Q_{peak}$ (33)

Therefore, the maximum capacity under the TIFR transmission policy for this case is given by

$$C_{TIFR} = \max(\gamma_0,\gamma_1)\left\{\log\left(1+\frac{min\{w_1(\gamma_1),w_2(\gamma_1)\}}{\sigma_2}\right)\cdot\left(1-\overline{K_0}+\overline{k_0}\exp\left(-\frac{\gamma_0}{\sigma^2}\right)-\frac{\overline{K_1}\sigma^2}{\gamma_1+\sigma^2}\right)\right\} \quad (34)$$

This result can be easily explained by the fact that the secondary user under the imposed constraints can transmit using infinite power; for γ1 → 0. For this reason, we choose to apply an (additional) average transmit power constraint as follows:

The maximum capacity under the TIFR transmission policy is now given by

$$C_{TIFR} = \max(\gamma_0,\gamma_1)\{(1-P_{out}(\gamma_0,\gamma_1))\cdot log\left(1+\frac{min\{w_1(\gamma_1),w_2(\gamma_1),w_3(\gamma_0,\gamma_1)\}}{\sigma^2}\right)\} \quad (35)$$

and the respective outage capacity for a target probability of outage Pout by

$$C_{out} = max(\gamma_0)\left\{\log(1+\frac{min\{\overline{w_3}(\gamma_0),\overline{w_2}(\gamma_0),\overline{w_3}(\gamma_0)\}}{\sigma^2})\cdot(1-\overline{P_{out}})\right\} \quad (36)$$

VI. RESULTS & DISCUSSIONS

In this dissertation work the following simulation results are obtained for the proposed cognitive radio system and compare it with the conventional spectrum sharing scheme.

A. Ergodic throughput

As discussed in the network model the channels g and h are considered to be the squared norms of independent circularly symmetric complex Gaussian (CSCG)random variables that are distributed as CN(0, 1) and CN(0, 10), respectively. The maximum average tolerable interference power at the primary receiver is considered to be Γ = 1,whereas an additional channel power gain attenuation is considered for the channel h between the secondary transmitter (SU-Tx)and the primary receiver (PU-Rx), where an attenuation of10 dB, for example, means that E{h} = 1.

In Fig. 6 , the ergodic throughput of the proposed and the conventional spectrum sharing scheme are presented versus the additional channel power gain attenuation between the secondary transmitter and the primary receiver for different values of the average transmit power Pavof the secondary users. It can be clearly seen from Fig. 6 that the ergodic throughput of the proposed cognitive radio system is significantly higher compared to the conventional spectrum sharing system, even for very low values of the channel power gain attenuation between the SU-Tx and the PR-Rx.

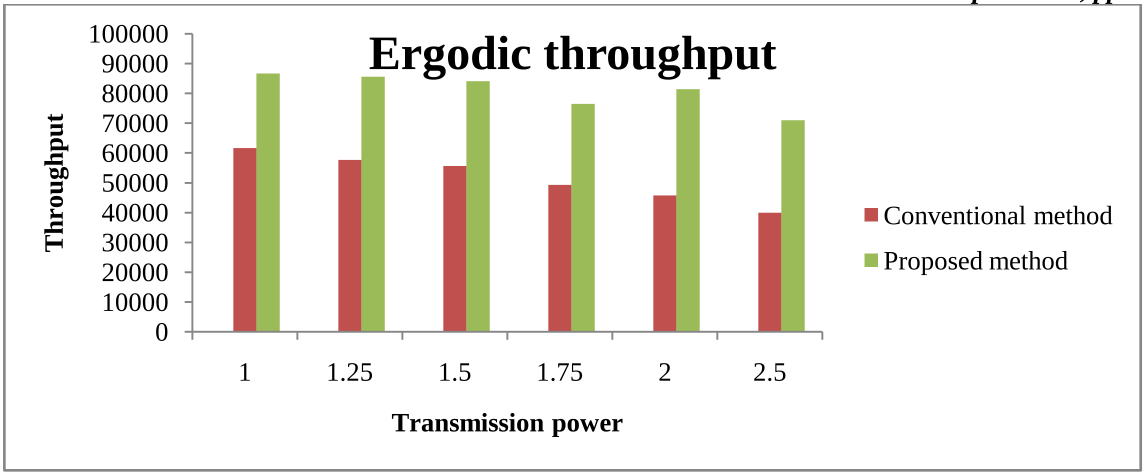

Fig 6 Comparision of Ergodic throughput for conventional and proposed spectrum sharing techniques

B. Outage capacity under TIFR transmission policy

Here outage capacity and the capacity under the TIFR transmission policy of the proposed cognitive radio system is discussed. The target outage probability is set to Pout = 0.1, and the maximum peak interference Qpeak is related to the average interference constraint Γ by ρ =Qpeak/Γ. Simulation setup considers ρ = 1.5,Pd= 0.9 and Pav= 20 dB.

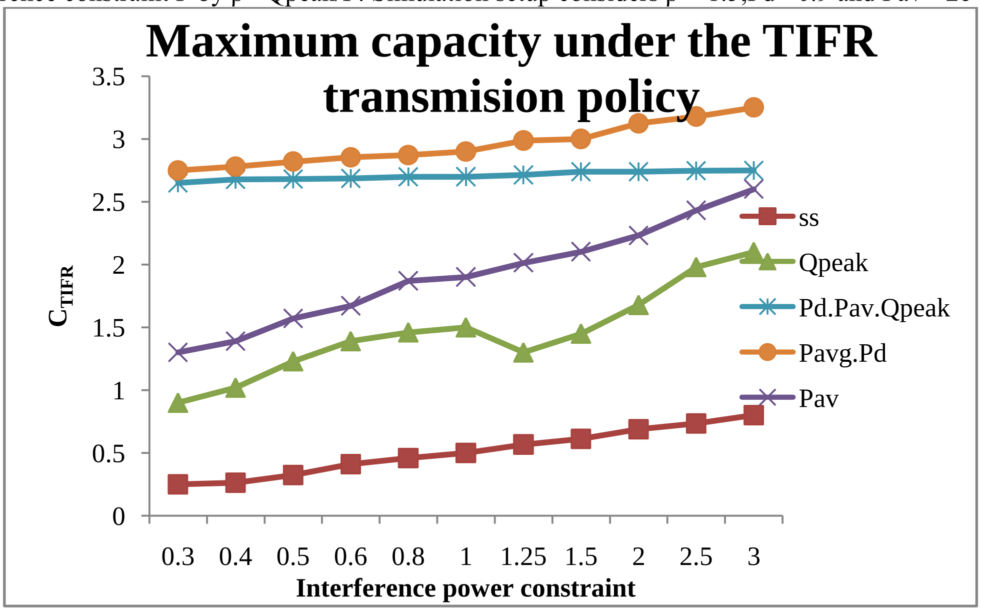

Fig 7 Comparision of outage capacity under TIFR transmission policy for different power constraints

In Fig. 7, the maximum capacity of the proposed and the conventional spectrum sharing scheme [11] under the TIFR transmission policy are presented versus the maximum average interference power Γ. The CTIFR capacity of the proposed spectrum sharing scheme is presented for the four cases study. These are distinguished in Fig 7 and 8 by the applied constraints which are denoted by Γ for the average interference power constraint, Pav for the average transmit power constraint, Qpeak for the peak interference power constraint, and Pd for the high target detection probability constraint. It can be clearly seen from Fig. 7 that the CTIFR capacity of the proposed spectrum sharing scheme is significantly higher compared to the conventional spectrum sharing, which can be easily explained the fact that the secondary users make a more efficient use of the available spectrum by employing a cognitive behaviour and obtaining the status (idle/active) of the frequency band, instead of "blindly" assuming that the primary users are always active. The proposed scheme offers an efficient way to perform spectrum sensing and adapt the transmit power based on the spectrum sensing decision, in order to protect the primary users from harmful interference. As expected and seen in Fig. 7, the capacity reduces when a peak interference power constraint is applied, whereas, interestingly, the capacity increases for the case that the opportunistic spectrum access approach is considered when the frequency band is detected to be idle,a high target detection probability is considered. This approach enables the secondary users to freely access the frequency band when it is detected tobe idle and this is what boosts the capacity for the cases undera high target detection probability Pd seen in Fig. 7.

C. Outage capacity for proposed spectrum sharing scheme

Here the outage capacity is presented in Fig. 8 for the proposed and the conventional spectrum sharing scheme. Similar remarks as in CTIFR capacity can be made for the outage capacity of the proposed scheme. The result shows that the outage capacity by this scheme is higher compared to the respective of the conventional spectrum sharing scheme, that a peak interference constraint reduces the achievable outage capacity, and finally, that the adoption of the opportunistic spectrum access approach for the case that the primary users are detected to be idle leads to a higher achievable outage capacity for the proposed spectrum sharing scheme.

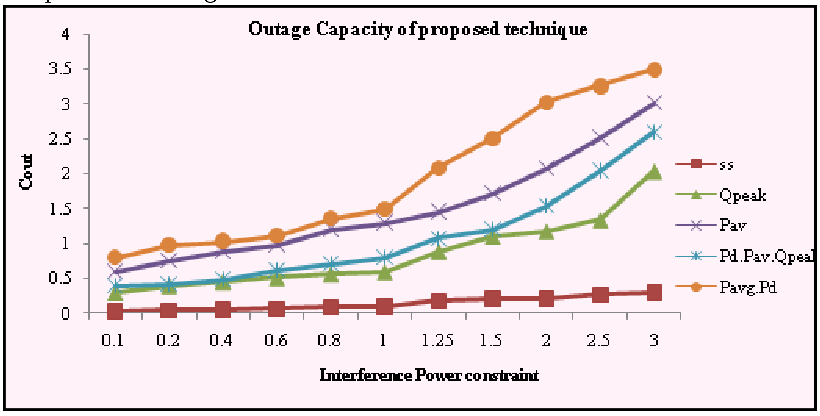

Fig 8 Comparision of outage capacity of proposed technique for different power constraints

VII. CONCLUSION

This dissertation work is proposed to maximize the throughput in cognitive radio network. It proposes an innovative spectrum sharing technique that will significantly improve achievable throughput of the network. This work introduces novel receiver and a frame structure for spectrum sharing in which spectrum sensing and data transmission is done simultaneously. The problem of optimal power allocation that maximizes the ergodic capacity of the system under average transmits and interference power constraints are also studied.This work also includes maximization of outage capacity under TIFR transmission policy and proposed spectrum sharing methodology.

Simulation results demonstrated that the proposed approach effectively provides increase in throughput .This proposed technique helps in improving the ergodic capacity by providing nearly 60 % increase in the throughput. This dissertation work also analyzes the outage capacity under various power constraints. Further network capacity comparison is also done considering standard TIFR transmission policy and proposed optimal power allocation technique.

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