Wireless Netw (2017) 23:519–531
DOI 10.1007/s11276-015-1172-0

Capacity in fading environment based on soft sensing information under spectrum sharing constraints

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Published online: 31 December 2015

Abstract In this paper, the ergodic channel capacity for a secondary user is investigated using soft sensing information about primary user activity in a shared channel under joint peak transmit power and average received interference power constraints for Nakagami-m fading channel. The results of the proposed power adaptation scheme illustrate the effect of communication environment parameters and soft sensing information about primary user activity on the channel capacity of secondary user. In particular, the effect of cross link channel state information to maximize the channel capacity for the power adaptation scheme is emphasized by considering the Lagrangian optimization problem for joint peak transmit power and average interference power constraints. Moreover, the performance of the primary user is also investigated considering the interference of the secondary user to the primary in spectrum sharing environment in terms of transmission rate and average channel capacity.

Keywords Cognitive radio · Fading · Spectrum sensing · Spectrum sharing · Power adaptation · Ergodic channel capacity

1 Introduction

Since, the wireless products have become an integral part of modern lifestyle; the twenty-first century has witnessed the rapid deployment of wireless devices and applications in market. All these bandwidth hungry applications have increased the demand of electromagnetic spectrum. Traditionally, spectrum allocation policy is very inflexible in a sense that frequency band are exclusively licensed to the user for long-term access with restriction on maximum transmission power to shield systems from mutual interference all the time. Since, most of the spectrum has already been assigned, it has become extremely difficult to find vacant frequency band to deploy new wireless applications or to enhance the existing ones. On contrary to the spectrum scarcity problem, a recent Federal Communication Commission (FCC) report is an eye opener to the entire communication industry worldwide and has revealed that a large chunk of bandwidth remained unutilized most of the time and the assigned spectra is being utilized sporadically due to a rigid spectrum allocation policy in use [1]. Today's spectrum usage is largely licensed access, while only a small part of the spectrum used for license free applications. In this licensed access approach, operators acquire spectrum over a large geographical area for a long-term basis and deploy communication networks to carry a range of services with predictable quality of service (QoS). This rigid spectrum allocation approach results into spectrum underutilization and has left almost no spectrum space for the successful deployment of future communication application [2].

In order to meet the growing data rate requirements of future communication applications, telecommunication industry needs to find new communication paradigms to access spectrum in addition to the existing licensed and license free applications. Cognitive Radio technology has evolved as a one of the promising technology that has a terrific potential to overcome this spectrum scarcity problem faced by communication industry today. The technology allows cognitive user, also known as secondary

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user, to be constantly aware of its surrounding environment and to adapt its communication parameters in such a manner that it may coexist with licensed primary users over a same channel without exceeding interference limit to the primary user [3]. To do so, two different approaches are used namely spectrum sharing and spectrum sensing. In spectrum sharing approach, both primary and secondary users may coexist over a same channel as long as interference experienced by primary user is below predefined threshold limit. Whereas, in spectrum sensing approach, cognitive user constantly monitors channel activity and transmit on finding channel vacant by primary user such that no interference caused to the licensed primary user. In this context, different channel state information (CSI) conditions were considered first time at transmitter and receiver, and the receiver side alone in [4] to propose an optimum adaptive power scheme and to estimate the fading channel capacity with an average power constraint only. Later, Khojastepour has investigated the ergodic capacity limit of fading channel under peak and average transmit power constraints [5]. Generally, secondary user uses CSI to adjust its transmission power to maximize channel capacity [6, 7]. Ghasemi and Sousa [6] have suggested that channel capacity for secondary user increased significantly by opportunistically transmitting at high power levels such that signal strength received at primary receiver is deeply faded. Leila and Sonia [7] have proposed optimal transmission scheme by exploiting secondary CSI and channel information between secondary Transmitter (STx) and Third party Receiver (e.g., the licensed primary receiver) under peak and average transmit power constraint at third party receiver. The channel capacity under received-power constraint at third party receiver was firstly considered by Gastpar [8] and derived the capacity of different AWGN channels with the average received-power constraint at third-party receiver. Zhang [9] has demonstrated that ergodic capacity of both primary as well as secondary users can be enhanced by considering primary and secondary CSI together. In practice, it is extremely difficult for secondary transmitter to have a direct access of primary link CSI. In [10] it has been suggested that in the absence of primary SCI, secondary receiver sensitivity can be used as a proxy to estimate distance between secondary transmitter and primary receiver to optimize transmission power level. In few recent works, the capability of cognitive radio to sense spectrum is used by secondary user to adapt its transmission parameters and therefore to maximize channel capacity. To do so, primary user activity is monitored through local signal processing at secondary user side by mounting sensing detector on secondary device [11]. Energy detection scheme is mostly employed to obtain this soft sensing information to detect the presence/absence of the primary user [12, 13]. In this context, Hamadi [14] has develop an approach to allow the cognitive radio to operate in the presence of the licensed user and in order to minimize the interference to the licensed user, the transmit power of the cognitive radio is controlled by using the side information of spectrum sensing. In [15] Srinivasa and Jafar have taken advantage of this sensing information to develop a non binary power control scheme to maximize the channel capacity of secondary user considering that secondary transmitter does not have prior information about CSI of its corresponding channel. The impact of imperfect spectrum sensing has also been considered by many researchers. For instance, Musavian and Aissa have investigated the ergodic and outage capacities for secondary user along with the development of optimum power allocation policies for Rayleigh flat-fading channels when only partial channel information of the link between the secondary's transmitter and primary's receiver is available to the secondary transmitter [16]. Rezki and Alouini has derived the ergodic capacity for a secondary link based on imperfect CSI knowledge at secondary transmitter under the average and peak transmit power constraints for Rayleigh fading channel [17]. Suraweera et al. [18] has investigated the impact of imperfect channel knowledge of the primary–secondary link on the SU mean capacity under a peak power constraint at the primary receiver. However, in [17, 18] different system capacities have been assessed for secondary user without using soft sensing information. In [19], ergodic capacity under Nakagami-*m* fading channel is investigated based on sensing parameter and CSI of secondary link under average interference power constraint whereas, peak transmission power of secondary user is ignored which results ergodic capacity to increase monotonically. However, to avoid health endangering situation and to restrict the secondary transmission power within the operating range of power amplifier, it is important to restrict secondary user transmission power with peak power constraint. Therefore, in this paper, we have investigated the ergodic channel capacity for a secondary user by using soft sensing information pertaining to the primary user activity under peak transmit power and average received power constraints for Nakagami-m fading channel and unlike [20], we have consider the fading between secondary transmitter and primary receiver in terms of channel gain ratio for adaptive transmission power scheme. The results of the work illustrate the effect of communication environment parameters and soft sensing information about primary user activity in shared channel on ergodic channel capacity of secondary user. The rest of the paper is organized as follows: the spectrum sharing system is described in Sect. 2. Ergodic capacity of secondary user under adaptive transmission policy is investigated for different communication environment parameters using soft sensing information for Nakagami-*m* fading channel in

Sect. 3. Finally, numerically computed results and discussion followed by conclusion is given in Sects. 4 and 5 respectively.

2 Spectrum sharing system

In this section, proposed spectrum sharing cognitive communication system is introduced, setup terminology and name the parameters of the environment are described for primary and secondary user direct and cross links. We have considered point to point communication between single primary and cognitive user. In a proposed spectrum sharing system there is one primary transmitter (PTx) that uses the wireless channel to transmit its information to the primary receiver (PRx). At the same time, there is one secondary transmitter (STx) and secondary receiver (SRx) that wishes to share this channel as long as interference inflicted on primary is less than predefined value as shown in Fig. 1.

The link between PTx and PRx and between STx and SRx are direct links (solid black lines) and between STx and SRx are cross links (solid red and blue lines). It has been assumed that the channel between PTx and PRx is a stationary block fading channel in which channel gain remains constant for coherence time period of T_c and then attains a new value [20]. Whereas, the channel between STx and SRx is assumed to be discrete time flat fading channel with perfect channel state information (CSI) available with STx and SRx pair in advance. The channel gain is $\sqrt{Y_s}$ between STx and SRx, $\sqrt{Y_p}$ between PTx and PRx, $\sqrt{Y_m}$ between PTx and STx and $\sqrt{Y_{sp}}$ between STx and PRx. All these channel power gains are independent and vary according to their distributions. We assume that primary transmitter PTx is situated far apart form secondary receiver SRx and therefore interference caused by it is treated as background noise at the secondary receiver. To calculate ergodic capacity, unit mean distribution is assumed for Y_s whereas for Y_m and Y_{sp} Nakagami-m distribution is assumed with

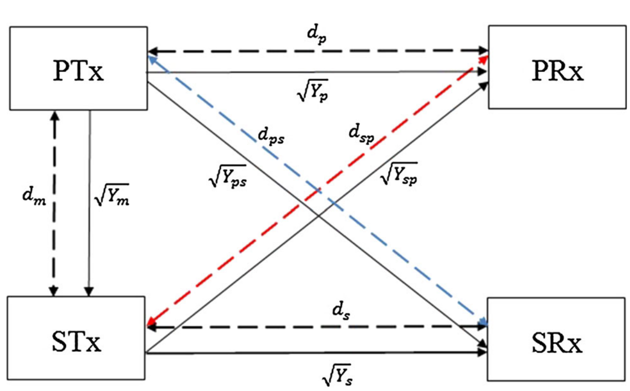

Fig. 1 Proposed spectrum sharing model

variances depend on the physical separation between associated nodes for example d_m^{-2} for Y_m, d_{sp}^{-2} for Y_{sp} etc. The channel between PTx and SRx is assumed to be additive white Gaussian noise (AWGN) channel with zero mean Gaussian random variable having variance N_0B where N_0 and B represents noise power spectral density and signal bandwidth respectively. All channel gains are assumed stationary, ergodic and mutually independent from noise.

2.1 Spectrum sensing module

Figure 2 shows the block diagram of secondary communication system in which STx is equipped with an energy detector that constantly monitors shared channel variations to know the presence or absence of the primary signal. Based on received signal strength from of incumbent user, it calculates a sensing metric ξ. Since PU activity follows block static model and therefore the test statics of ξ remains unchanged for the period of T_c [20]. Accordingly, one may consider PU active in its licensed band with probability P_b or inactive with probability $\bar{P}_b = 1 - P_b$ for T_c time duration. These test statics are used to estimate the primary user's activity being in ON or OFF state and the parameter ξ can be modeled according to the Chi- square probability distribution functions (PDFs) with v degree of freedom which further depends on the number of samples used in the sensing duration N. According to [21], p. 941], for $v \geq$ 30, Chi square PDF is approximately equals to Gaussian PDF, we have assumed that sensing metric has Gaussian PDF with numbers of observation samples equal to 30. Based on primary user activity being ON or OFF, the PDFs of ξ are defined as $f_{on}(\xi) \sim N\left(\mu_{on}, \delta^2_{on}\right)$ and $f_{off}(\xi) \sim N\left(\mu_{off}, \delta^2_{off}\right)$ respectively and given by [22]

$$f_{on}(\xi)_{PUActive} \sim N\left(\mu_{on}, \delta^2_{on}\right) \quad where \begin{cases} \mu_{on} = N\left(\dfrac{P_t}{d_m^2} + 1\right) \\ \delta^2_{on} = 2N\left(\dfrac{P_t}{d_m^2} + 1\right)^2 \end{cases} \tag{1}$$

$$f_{off}(\xi)_{PUidle} \sim N\left(\mu_{off}, \delta^2_{off}\right) \quad where \begin{cases} \mu_{off} = N \\ \delta^2_{off} = 2N \end{cases} \tag{2}$$

where, P_t is the average transmission power. The probability distributions of $f_{on}(\xi)_{PUActive}$ and $f_{off}(\xi)_{PUidle}$ will be given by

$$f_{off}(\xi) = \frac{1}{\sqrt{2\pi\delta^2_{off}}} exp\left(\frac{-\left(\xi - \mu_{off}\right)^2}{2\delta^2_{off}}\right) \tag{3}$$

$$f_{on}(\xi) = \frac{1}{\sqrt{2\pi\delta^2_{on}}} exp\left(\frac{-\left(\xi - \mu_{on}\right)^2}{2\delta^2_{on}}\right) \tag{4}$$

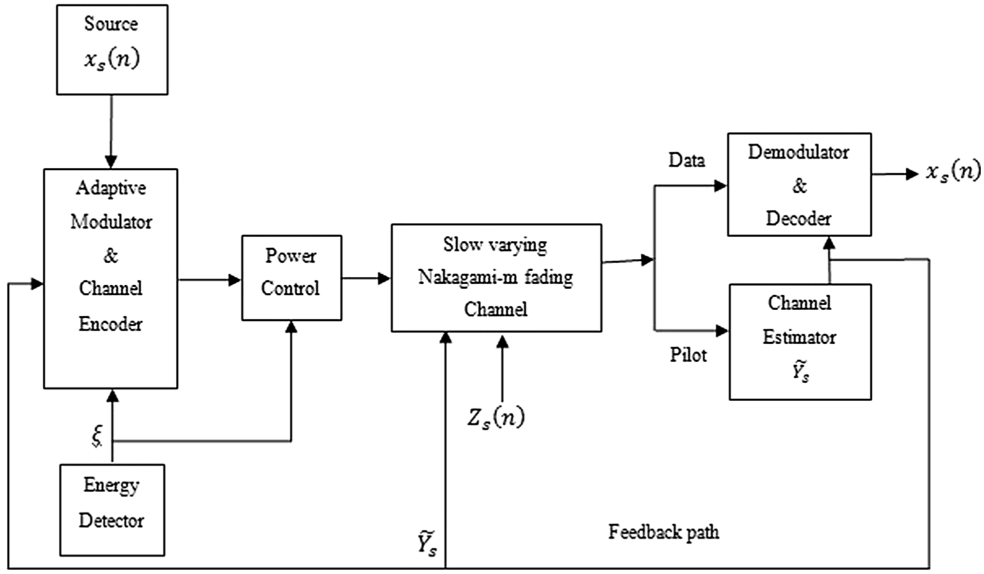

Fig. 2 Block diagram of secondary communication system

Based on the test statistics from energy detector given in (3) and (4), STx must adjust its transmission power optimally to satisfy predefined power constraint while maintaining QoS requirement for the primary user. Under spectrum sharing scenario, when PU is active, the transmission of STx must be limited by a constraint known as average interference power constraint, to restrict the amount of interference at primary receiver from secondary transmitter. The constraint may be defines as

$$E_{\gamma_s,\gamma_{sp},\xi}\left[P(\gamma_s,\gamma_{sp},\xi)\gamma_{sp}\right]_{PUActive} \le P_{Inter}; \quad \forall \gamma_s,\gamma_{sp},\xi \tag{5}$$

The maximum transmission power of STx is restricted under peak power constraint and may be defined as

$$P(\gamma_s,\gamma_{sp},\xi) \le P_{Peak}; \quad \forall \gamma_s,\xi \tag{6}$$

where, $E_{\gamma_s,\gamma_{sp},\xi}[\cdot]$ defines expectation operator over the joint PDFs of random variable γ_s,γ_{sp} and ξ. $P(\gamma_s,\gamma_{sp},\xi)$ is instantaneous transmission power of STx, P_{Inter} is the average interference power constraint at primary receiver and P_{Peak} is maximum transmission power constraint on secondary transmitter.

3 Capacity analysis for secondary user under power adaptation scheme

The ergodic capacity is good performance indicator for delay-insensitive services and may be defined as maximum achievable rate averaged over all the fading blocks with arbitrary small probability of error [23]. In [19], ergodic capacity for Nakagami fading channel is investigated based on sensing statistics and CSI of secondary link under average interference constraint with no peak power restriction of secondary user. However, the secondary user transmission power must be limited within the operating range of power amplifier and to avoid health endangering situation. In this paper, peak transmission power constraint is also imposed on secondary user and ergodic channel capacity for power adaptation scheme is investigated under average interference power and peak transmission power constraint in which STx transmission power varies according to

a. Soft sensing metric (ξ),
b. Direct channel power gain between STx and SRx (Y_s), and
c. Cross channel power gain between STx and PRx (Y_{sp}).

In fading environment, following same line of development as in [19], it is straightforward to show that channel capacity can be achieved with optimum power distribution such that both the constraints are satisfied. Assuming Y_s and Y_{sp} are independent to each other, the channel capacity becomes the solution of the following optimization problem

$$C_{er} = \max_{P(Y_s,Y_{sp},\xi)\ge 0} \iiint B\log_2\left(1+\frac{P(Y_s,Y_{sp},\xi)Y_s}{N_0B}\right) Y_u(\xi)f_s(Y_s)f_{sp}(Y_{sp})f_{on}(\xi)dY_s dY_{sp} d\xi \tag{7}$$

Subject to

$$\iiint P(Y_s,Y_{sp},\xi)Y_{sp}f_s(Y_s)f_{sp}(Y_{sp})f_{on}(\xi)dY_s dY_{sp} d\xi \le P_{Inter} \tag{8}$$

and,

$$P(Y_s, Y_{sp}, \xi) \le P_{Peak} \quad (9)$$

where, $P(Y_s, Y_{sp}, \xi)$ is secondary transmission power and is a joint PDF of secondary channel direct and cross link power gains and sensing metric ξ. To obtain optimal power allocation for $P(Y_s, Y_{sp}, \xi)$, the Lagrangian function can be formed as

$$\begin{aligned} &L\left(P(Y_s, Y_{sp}, \xi), \lambda_1, \lambda_2(Y_s, Y_{sp}, \xi), (Y_s, Y_{sp}, \xi)\right) \\ &= \iiint \log_2\left(1 + \frac{P(Y_s, Y_{sp}, \xi) Y_s}{N_0 B}\right) Y_u(\xi) f_s(Y_s) \\ &\times f_{sp}(Y_{sp}) f_{on}(\xi) dY_s dY_{sp} d\xi \\ &- \lambda_1 \left[\iiint P(Y_s, Y_{sp}, \xi) Y_{sp} f_s(Y_s) f_{sp}(Y_{sp}) \right. \\ &\left. \times f_{on}(\xi) dY_s dY_{sp} d\xi - P_{Inter} \right] \\ &+ \iiint \lambda_2(Y_s, Y_{sp}, \xi) P(Y_s, Y_{sp}, \xi) dY_s dY_{sp} d\xi \\ &- \iiint \lambda_3(Y_s, Y_{sp}, \xi)\left[P(Y_s, Y_{sp}, \xi) - P_{Peak}\right] dY_s dY_{sp} d\xi \end{aligned} \quad (10)$$

where, $\lambda_1, \lambda_2(Y_s, Y_{sp}, \xi), \lambda_3(Y_s, Y_{sp}, \xi)$ are Lagrangian multipliers and can be calculated such that constraint in (8) satisfied. Since, $L(, \lambda_1, \lambda_2(Y_s, Y_{sp}, \xi), \lambda_3(Y_s, Y_{sp}, \xi))$ is a concave function of $P(Y_s, Y_{sp}, \xi)$ and interference constraint defined in (9) is a convex function, the derivative of Lagrangian function in (10) w.r.t. $P(Y_s, Y_{sp}, \xi)$ and setting it to zero will give

$$\begin{aligned} &\frac{1}{1 + \frac{P(Y_s, Y_{sp}, \xi) Y_s}{N_0 B}} \frac{Y_s}{N_0 B} Y_u(\xi) f_s(Y_s) f_{sp}(Y_{sp}) f_{on}(\xi) \\ &- \lambda_1 Y_{sp} f_s(Y_s) f_{sp}(Y_{sp}) f_{on}(\xi) + \lambda_2(Y_s, Y_{sp}, \xi) \\ &- \lambda_3(Y_s, Y_{sp}, \xi) = 0 \end{aligned}$$

or

$$\begin{aligned} &\left[\frac{Y_u(\xi) Y_s}{P(Y_s, Y_{sp}, \xi) Y_s + N_0 B} - \lambda_1 Y_{sp}\right] f_s(Y_s) f_{sp}(Y_{sp}) f_{on}(\xi) \\ &- \lambda_2(Y_s, Y_{sp}, \xi) - \lambda_3(Y_s, Y_{sp}, \xi) = 0 \end{aligned} \quad (11)$$

For optimum power allocation, (11) must satisfy 1st order Karush–Kuhn–Tucker (KKT) conditions as defined below

$$\begin{aligned} &Condition\,1: \ \lambda_1 \left[\iiint P(Y_s, Y_{sp}, \xi) Y_{sp} f_s(Y_s) f_{sp} \right. \\ &\left. (Y_{sp}) f_{on}(\xi) dY_s dY_{sp} d\xi - P_{Inter} \right] = 0 \end{aligned} \quad (12)$$

$$Condition\,2: \ \lambda_2(Y_s, Y_{sp}, \xi) P(Y_s, Y_{sp}, \xi) = 0 \quad (13)$$

$$Condition\,3: \ \lambda_3(Y_s, Y_{sp}, \xi)\left[P(Y_s, Y_{sp}, \xi) - P_{Peak}\right] = 0 \quad (14)$$

For optimum power control condition $0 \le P(Y_s, Y_{sp}, \xi) \le P_{Peak}$ must be satisfied for all the values of Y_s, Y_{sp} and ξ.

Three different cases arise therefore

Case 1: $P(Y_s, Y_{sp}, \xi) = 0$ for some values of Y_s, Y_{sp} and ξ. This requires $\lambda_3(Y_s, Y_{sp}, \xi) = 0$ in (14) and $\lambda_2(Y_s, Y_{sp}, \xi) \ge 0$ in (13). Solving (11) with these conditions yields

$$\begin{aligned} &\frac{Y_s}{N_0 B} - \lambda_1 Y_{sp} < 0 \\ &\frac{Y_u(\xi)}{N_0 B Y_{sp} \lambda_1} < \frac{1}{Y_s} \end{aligned} \quad (15)$$

Case 2: $P(Y_s, Y_{sp}, \xi) = P_{Peak}$ for some values of Y_s, Y_{sp} and ξ. This requires $\lambda_3(Y_s, Y_{sp}, \xi) \ge 0$ in (14) and $\lambda_2(Y_s, Y_{sp}, \xi) = 0$ in (13). Solving (11) with these conditions will give

$$\begin{aligned} &\frac{Y_u(\xi) Y_s}{P_{Peak} Y_s + N_0 B} - \lambda_1 Y_{sp} > 0 \\ &\frac{\frac{Y_u(\xi)}{\lambda_1 Y_{sp}} - P_{Peak}}{N_0 B} > \frac{1}{Y_s} \\ &\frac{Y_v(\xi)}{N_0 B} > \frac{1}{Y_s} \end{aligned} \quad (16)$$

where,

$$\begin{aligned} &Y_v(\xi) = \frac{Y_u(\xi)}{\lambda_1 Y_{sp}} - P_{Peak} \quad \text{and} \\ &Y_u(\xi) = P_b + \bar{P}_b \frac{f_{off}(\xi)}{f_{on}(\xi)} \end{aligned} \quad (17)$$

Case 3: $0 \le P(Y_s, Y_{sp}, \xi) \le P_{Peak}$ for some values of Y_s, Y_{sp} and ξ. This requires $\lambda_3(Y_s, Y_{sp}, \xi) = \lambda_2(Y_s, Y_{sp}, \xi) = 0$.

Using this, solution of (11) becomes

$$\begin{aligned} &\frac{Y_u(\xi) Y_s}{P(Y_s, Y_{sp}, \xi) Y_s + N_0 B} - \lambda_1 Y_{sp} = 0 \\ &\frac{Y_u(\xi)}{\lambda_1 Y_{sp}} = P(Y_s, Y_{sp}, \xi) + \frac{N_0 B}{Y_s} \\ &P(Y_s, Y_{sp}, \xi) = \frac{Y_u(\xi)}{\lambda_1 Y_{sp}} - \frac{N_0 B}{Y_s} \end{aligned} \quad (18)$$

Therefore, the power adaptation scheme will be given as

$$P\left(Y_s, Y_{sp}, \xi\right) = \begin{pmatrix} P_{Peak} & \dfrac{1}{Y_s} \leq \dfrac{Y_v(\xi)}{N_0B} \\ \dfrac{Y_u(\xi)}{\lambda_1 Y_{sp}} - \dfrac{N_0B}{Y_s} & \dfrac{Y_v(\xi)}{N_0B} \leq \dfrac{1}{Y_s} \leq \dfrac{Y_u(\xi)}{\lambda_1 Y_{sp} N_0 B} \\ 0 & \dfrac{1}{Y_s} > \dfrac{Y_u(\xi)}{\lambda_1 Y_{sp} N_0 B} \end{pmatrix} \tag{19}$$

Depending upon channel inversion $\left(\frac{1}{Y_s}\right)$, power adaptation scheme is divided into three parts with respect to two threshold values $\frac{Y_v(\xi)}{N_0B}$ and $\frac{Y_u(\xi)}{\lambda_1 Y_{spN_0B}}$. From (19), it can be observed that unlike [19] transmission is limited to peak value when channel inversion is weaker than $\frac{Y_v(\xi)}{N_0B}$. In other words, from (17) and (19) it is clear that, when fading between secondary transmitter and primary and secondary receivers is deep, STx can transmit with maximum power i.e. P_{Peak}. The second part represents the optimum transmission power for $\frac{Y_v(\xi)}{N_0B} \leq \frac{1}{Y_s} \leq \frac{Y_u(\xi)}{\lambda_1 Y_{sp} N_0 B}$. It shows that STx can transmit at higher power levels if Y_s increases and Y_{sp} decreases and therefore average interference power constraint between STx and PRx satisfied. Secondary user may take an advantage of fading channel conditions of primary user to transmit at high power levels and can enhance its ergodic channel capacity. From the third part of (19), it is clear that transmission of STx is suspended if channel inversion becomes stronger than $\frac{Y_u(\xi)}{\lambda_1 Y_{sp} N_0 B}$. The value of Lagrangian multiplier (λ_1) can be determined by putting (19) in (8) as

$$\iiint_{\frac{Y_v(\xi)}{N_0B}}^{\frac{Y_u(\xi)}{\lambda_1 Y_{sp} N_0 B}} \left(\frac{Y_u(\xi)}{\lambda_1 Y_{sp}} - \frac{N_0B}{Y_s}\right) Y_{sp} f_s(Y_s) f_{sp}\left(Y_{sp}\right) f_{on}(\xi) dY_s dY_{sp} d\xi + \iiint_0^{\frac{Y_v(\xi)}{N_0B}} P_{Peak} Y_{sp} f_s(Y_s) f_{sp}\left(Y_{sp}\right) f_{on}(\xi) dY_s dY_{sp} d\xi = P_{Inter} \tag{20}$$

$$\iiint_{\frac{Y_v(\xi)}{N_0B}}^{\frac{Y_u(\xi)}{\lambda_1 Y_{sp} N_0 B}} \left(\frac{Y_u(\xi)}{\lambda_1 N_0 B} - \frac{Y_{sp}}{Y_s}\right) f_s(Y_s) f_{sp}\left(Y_{sp}\right) f_{on}(\xi) dY_s dY_{sp} d\xi + \iiint_0^{\frac{Y_v(\xi)}{N_0B}} P_{Peak} \frac{Y_{sp}}{N_0B} f_s(Y_s) f_{sp}\left(Y_{sp}\right) f_{on}(\xi) dY_s dY_{sp} d\xi = \frac{P_{Inter}}{N_0B} = \psi$$

$$\iiint_{\frac{Y_v(\xi)}{N_0B}}^{\frac{Y_u(\xi)}{\lambda_1 Y_{sp} N_0 B}} \left(Y_u(\xi)\Upsilon_1 - \frac{Y_{sp}}{Y_s}\right) f_s(Y_s) f_{sp}\left(Y_{sp}\right) f_{on}(\xi) dY_s dY_{sp} d\xi + \iiint_0^{\frac{Y_v(\xi)}{N_0B}} P_{Peak} \frac{Y_{sp}}{N_0B} f_s(Y_s) f_{sp}\left(Y_{sp}\right) f_{on}(\xi) dY_s dY_{sp} d\xi = \frac{P_{Inter}}{N_0B} = \psi \tag{21}$$

where, $\Upsilon_1 = \frac{1}{\lambda_1 N_0 B}$ and $\psi = \frac{P_{Inter}}{N_0 B}$ is an average signal to noise ratio [24]. By putting (19) in (7), the expression of SU ergodic capacity can be obtained as

$$\begin{aligned} C_{er} = \max_{P\left(Y_s, Y_{sp}, \xi\right) \geq 0} \Bigg[& \iiint_0^{\frac{Y_v(\xi)}{N_0B}} B\log_2\left(1 + \frac{P_{Peak} Y_s}{N_0B}\right) Y_u(\xi) f_s(Y_s) f_{sp}\left(Y_{sp}\right) f_{on}(\xi) dY_s dY_{sp} d\xi \\ & + \iiint_{\frac{Y_v(\xi)}{N_0B}}^{\frac{Y_u(\xi)}{\lambda_1 Y_{sp} N_0 B}} B\log_2\left(1 + \frac{Y_s}{N_0B}\left(\frac{Y_u(\xi)}{\lambda_1 Y_{sp}} - \frac{N_0B}{Y_s}\right)\right) Y_u(\xi) f_s(Y_s) f_{sp}\left(Y_{sp}\right) f_{on}(\xi) dY_s dY_{sp} d\xi \Bigg] \\ C_{er} = \max_{P\left(Y_s, Y_{sp}, \xi\right) \geq 0} \Bigg[& \iiint_0^{\frac{Y_v(\xi)}{N_0B}} B\log_2\left(1 + \frac{P_{Peak} Y_s}{N_0B}\right) Y_u(\xi) f_s(Y_s) f_{sp}\left(Y_{sp}\right) f_{on}(\xi) dY_s dY_{sp} d\xi \\ & + \iiint_{\frac{Y_v(\xi)}{N_0B}}^{\frac{Y_u(\xi)}{\lambda_1 Y_{sp} N_0 B}} B\log_2\left(\frac{Y_s Y_u(\xi)}{N_0 B \lambda_1 Y_{sp}}\right) Y_u(\xi) f_s(Y_s) f_{sp}\left(Y_{sp}\right) f_{on}(\xi) dY_s dY_{sp} d\xi \Bigg] \end{aligned} \tag{22}$$

$$C_{er} = E_{Y_s,Y_{sp},\xi}\left[Blog_2\left(1+\frac{P_{Peak}Y_s}{N_0B}\right)\right] + E_{Y_s,Y_{sp},\xi}\left[Blog_2\left(\frac{Y_sY_u(\xi)}{N_0B\lambda_1Y_{sp}}\right)\right] \quad (23)$$

In terms of average interference power constraint, (23) may be written as

$$C_{er} = E_{Y_s,Y_{sp},\xi}\left[Blog_2\left(1+\frac{\rho.P_{Inter}Y_s}{N_0B}\right)\right] + E_{Y_s,Y_{sp},\xi}\left[Blog_2\left(\frac{Y_sY_u(\xi)}{N_0B\lambda_1Y_{sp}}\right)\right] \quad (24)$$

where, $\rho = \frac{P_{Peak}}{P_{Inter}}$.

3.1 Nakagami-m fading channel

In this section, ergodic channel capacity is investigated for different channel statistics. The most widely used fading channel model is Nakagami-m distribution to approximate urban indoor and outdoor environment multipath propagation by adjusting a single parameter m. The parameter measures the ratio of line of sight (LOS) signal component power to that of the multipath signal power [25, 26]. In general, for a unit mean channel gain

$$f_{\sqrt{Y}}(Y) = \frac{2m^mY^{2m-1}}{\Gamma(m)}e^{-mY^2}$$

For Nakagami-m fading channel, the channel power gain Y_s and Y_{sp} distributed according to the following gamma distribution [27]. Where, $\Gamma(.)$ is a gamma function and defined as $\Gamma(x) = \int_0^\infty t^{x-1}e^{-t}dt$. For channel power gains Y_s and Y_{sp} distributed according to

$$f_Y(Y) = \frac{m^mY^{m-1}}{\Gamma(m)}e^{-mY}. \quad (25)$$

For channel power gains Y_s and Y_{sp} distributed according to (25) with their m parameter m_0 and m_1 respectively, the joint PFD of $f_s(Y_s)f_{sp}(Y_{sp})$ will be given by

$$f_s(Y_s)f_{sp}(Y_{sp}) = \left(\frac{m_0}{m_1}\right)^{m_0}\frac{Y^{m_1-1}}{\beta(m_0,m_1)\left(Y+\frac{m_0}{m_1}\right)^{m_{0+m_1}}} \quad (26)$$

where, $\beta(a,b)$ is a beta function and defined as

$$\beta(a,b) = \frac{\Gamma(a)\Gamma(b)}{\Gamma(a+b)}$$

For $m_0 = m_1 = m$, (26) becomes

$$f_s(Y_s)f_{sp}(Y_{sp}) = \frac{Y^{m-1}}{\beta(m,m)(Y+1)^{2m}}. \quad (27)$$

where, $Y = \frac{Y_s}{Y_{sp}}$, using (27), the ergodic channel capacity from (22), under average interference and received power cstraint for Nakagami-m fading channel will be given as

$$C_{er} = \max_{P(Y_s,Y_{sp},\xi)\geq 0}\left[\iiint_0^{\frac{Y_v(\xi)}{N_0B}} Blog_2\left(1+\frac{P_{Peak}Y_s}{N_0B}\right)\frac{Y^{m-1}Y_u(\xi)}{\beta(m,m)(Y+1)^{2m}}f_{on}(\xi)dY_sdY_{sp}d\xi + \iiint_{\frac{Y_v(\xi)}{N_0B}}^{\frac{Y_u(\xi)}{\lambda_1Y_{sp}N_0B}} Blog_2\left(\frac{Y_sY_u(\xi)}{N_0B\lambda_1Y_{sp}}\right)\frac{Y^{m-1}Y_u(\xi)}{\beta(m,m)(Y+1)^{2m}}f_{on}(\xi)dY_sdY_{sp}d\xi\right] \quad (28)$$

Rayleigh and Rician fading is a special case of Nakagami-m fading with $m = 1$ and $m \geq 2$ respectively. Therefore, by putting $m = 1$, the ergodic capacity for Rayleigh fading channel will be given as

$$C_{er} = \max_{P(Y_s,Y_{sp},\xi)\geq 0}\left[\iiint_0^{\frac{Y_v(\xi)}{N_0B}} Blog_2\left(1+\frac{P_{Peak}Y_s}{N_0B}\right)\frac{Y_u(\xi)f_{on}(\xi)}{(Y+1)^2}dY_sdY_{sp}d\xi + \iiint_{\frac{Y_v(\xi)}{N_0B}}^{\frac{Y_u(\xi)}{\lambda_1Y_{sp}N_0B}} Blog_2\left(\frac{Y_sY_u(\xi)}{N_0B\lambda_1Y_{sp}}\right)\frac{Y_u(\xi)f_{on}(\xi)}{(Y+1)^2}dY_sdY_{sp}d\xi\right] \quad (29)$$

Similarly, by putting $m = 2$, the ergodic capacity for Rician fading channel will be given as

$$C_{er} = \max_{P(Y_s, Y_{sp}, \xi) \geq 0} \left[\iiint_0^{\frac{Y_v(\xi)}{N_0 B}} B\log_2\left(1 + \frac{P_{Peak} Y_s}{N_0 B}\right) \frac{6 Y_u(\xi) f_{on}(\xi)}{(Y+1)^4} dY_s dY_{sp} d\xi + \iiint_{\frac{Y_v(\xi)}{N_0 B}}^{\frac{Y_u(\xi)}{\lambda_1 Y_{sp} N_0 B}} B\log_2\left(\frac{Y_s Y_u(\xi)}{N_0 B \lambda_1 Y_{sp}}\right) \frac{6.Y_u(\xi) f_{on}(\xi)}{(Y+1)^4} dY_s dY_{sp} d\xi \right] \quad (30)$$

4 Capacity analysis for primary user under power adaptation scheme

In this section, the impact of cognitive communication is investigated on the performance of primary user. The performance metrics considered for the primary user in spectrum sharing cognitive environment are data transmission rate and average channel capacity under outage probability constraint.

From Fig. 1, it is clear that the received power at secondary receiver from primary user is $P_t Y_{ps}$ while from secondary transmitter is $P(Y_s, Y_{sp}, \xi) Y_s$. Therefore, signal plus interference ratio (SINR) of the primary user will be given by

$$\gamma = \frac{P_t Y_{ps}}{P(Y_s, Y_{sp}, \xi) Y_s + \sigma^2} = \frac{P_t Y_{ps}}{P(Y_s, Y_{sp}, \xi) Y_s} \quad (31)$$

Since, $(Y_s, Y_{sp}, \xi) Y_s \gg \sigma^2$. The probability density function (PDF) and cumulative distribution function (CDF) of γ will be given by (32) and (34)

$$f_\gamma(z) = \frac{P_t}{P(Y_s, Y_{sp}, \xi)} \frac{1}{\left(z + \frac{P_t}{P(Y_s, Y_{sp}, \xi)}\right)^2} \quad (32)$$

The cumulative distribution function (CDF) will be given by

$$F_\gamma(z) = \frac{z}{z + \frac{P_t}{P(Y_s, Y_{sp}, \xi)}} \quad (33)$$

If R is the primary user transmission rate, the outage probability (δ) of primary user may be given as

$$P\{\log_2(1+\gamma) \leq R\} \leq \delta \quad \text{or} \quad F_\gamma(2^R - 1) = \delta \quad (34)$$

Replacing z by $2^R - 1$ in (33), we get

$$\frac{2^R - 1}{(2^R - 1) + \frac{P_t}{P(Y_s, Y_{sp}, \xi)}} = \frac{2^R - 1}{(2^R - 1) + \bar{\gamma}} \leq \delta \quad (35)$$

where $\bar{\gamma} = \frac{P_t}{P(Y_s, Y_{sp}, \xi)}$ known as average SINR of primary user. When secondary user transmits at maximum power without violating outage probability of primary user, the average channel capacity of primary user will be given by

$$C_{er\_Primary} = \log_2\left(1 + \frac{\delta}{1-\delta}\gamma\right) = \log_2\left(1 + \frac{\delta}{1-\delta} \frac{P_t}{P(Y_s, Y_{sp}, \xi)}\right) \quad (36)$$

The average channel capacity of primary user will be given by $\bar{C}_{er} = E[\log_2(1+\gamma)]$, where E [.] is the expectation operator. Thus, for given $\bar{\gamma}$, average channel capacity for primary user is

$$\bar{C}_{er} = \begin{cases} \frac{\bar{\gamma}}{\bar{\gamma}+1} \log_2(\bar{\gamma}) & \bar{\gamma} \neq 1 \\ \log_2 & \bar{\gamma} = 1 \end{cases}. \quad (37)$$

When no interference is experienced by primary user from cognitive user, signal to noise ratio of the primary is given by $\gamma = \frac{P_t Y_{ps}}{\sigma^2}$ and the average channel capacity of primary user is given by

$$\bar{C}_{er} = \log_2(e) \exp\left(\frac{1}{\bar{\gamma}}\right) E_1\left(\frac{1}{\bar{\gamma}}\right). \quad (38)$$

where, $E_1(.)$ is the exponential integral and is given by $E_1(z) = \int_z^\infty x^{-1} e^{-x} dx$.

5 Results and discussion

In this section proposed power control scheme is evaluated numerically when a spectrum sharing system operates under peak transmit power and average received interference power constraint for Nakagami-m fading channel model as presented in Sect. 3. As shown in Fig. 1, it has been assumed that nodes are placed in such a manner that $d_s = d_p = 1$ and $d_m = 3$. The channel variations for γ_s and γ_{sp} are modeled through Nakagami PDFs and $N_0 B$ is assumed to be unity.

The energy detection scheme is employed to estimate the presence or absence of the primary user in a channel due to the ease in implementation and low computational complexities [14]. It estimates sensing metric in with samples $N = 30$. The PU transmission power is set $P_t = 1$ with an assumption that PU keeps channel occupied for half of the time and free for remaining half i.e. $P_b = 0.5$.

3(a) shows the variation of the sensing PDFs $f_{off}(\xi)$ and $f_{on}(\xi)$ in accordance to the sensing metric ξ. The same is used to compute the parameter $Y_u(\xi)$ and is shown in Fig. 3(b). The variation of $Y_u(\xi)$ can be divided into three different regions i.e. $Y_u(\xi) > 1$, $Y_u(\xi) = 1$ and $Y_u(\xi) < 1$ depending upon the probability of PU being ON or OFF. As shown in Fig. 3(b), $Y_u(\xi) > 1$ region represents that the probability of PU to be inactive in a channel is higher otherwise $Y_u(\xi) < 1$. Whereas, $Y_u(\xi) = 1$ represents a scenario when SU has no soft sensing information of PU activity in a channel and therefore assumed that PU is all time active with $P_b = 1$. From the variation of $Y_u(\xi)$, it is anticipated that SU can transmit at higher power levels to achieve high ergodic capacity under condition $Y_u(\xi) > 1$ and lesser for $Y_u(\xi) < 1$.

Figure 4 shows the impact of the channel variations and soft sensing information on the instantaneous transmission power of secondary user while satisfying the average received interference power and peak transmit power constraints. As expected, secondary user transmits at higher power levels when the probability of primary user being OFF is high i.e. $Y_u(\xi) > 1$ and its CSI is strong and lower its transmission power as the probability of primary user being ON in licensed channel increases i.e. $Y_u(\xi) < 1$. Here, the results have been simulated for $P_{Inter} = -6dB$ and $P_{Peak} = 0dB$ to satisfy both the constraints at PRx and STx respectively.

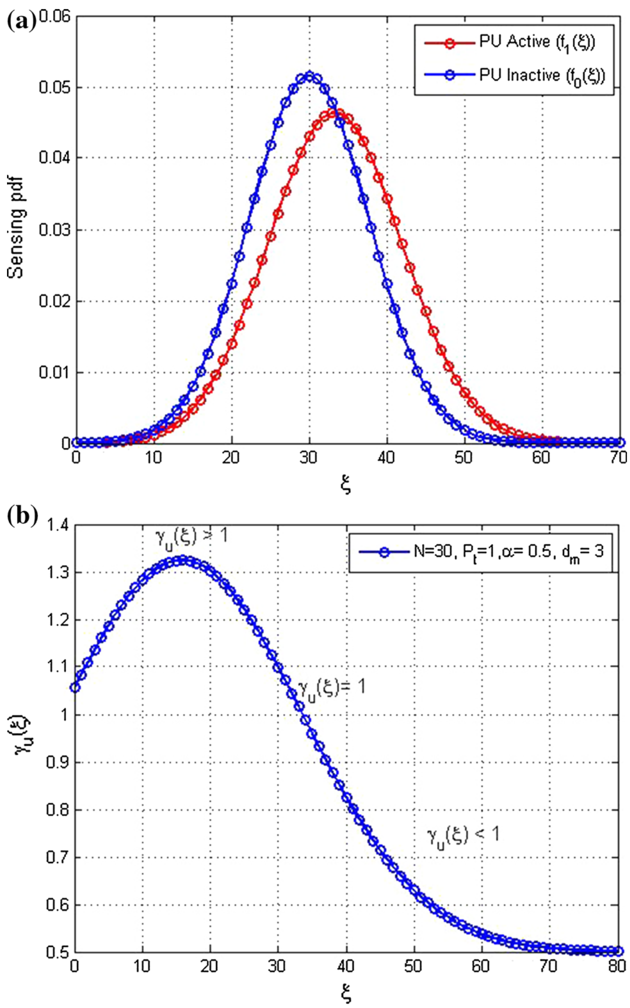

Fig. 3 **a** Sensing PFDs to estimate PU's activity in a channel **b** $Y_u(\xi)$ variation [20]

For Nakagami-m fading channel with $m = 1$ (Rayleigh fading) and $m = 2$ (Rician fading), illustration of the ergodic channel capacity for secondary user verses P_{Inter} for different values of ρ is carried out in Figs. 5 and 6 respectively. We have also illustrated a case with no peak transmission power constraint is imposed on secondary user as in [19]. The figures show that for the fixed value of ρ and therefore under peak transmission constraint on SU, the ergodic capacity can be increased if the primary user increases its average interference tolerance limit without exceeding outage value.

Moreover, from (24) and figures, it is clear that for a given average interference power constraint, the secondary user ergodic capacity increases by increasing ρ i.e. by increasing peak transmission power and converge towards a case when no peak power constraint is imposed on secondary user. It means secondary user must consider higher P_{Peak} value for transmission to enhance the channel capacity, but for much higher values of P_{Peak}, the channel capacity is limited by average interference power constraint of primary user and its channel gain and cannot be enhance further by increase its peak transmission power.

Further, comparison between Figs. 5 and 6 reveals that under joint peak transmission power and average received interference power constraint, channel capacity in the former case is higher than latter due to the strict restrictive nature of the received interference constraint imposed by primary.

Figures 7 and 8 show the channel capacity verses channel gain ratio under Rayleigh and Nakagami-m fading $(m = 2)$ channel with average interference constraint

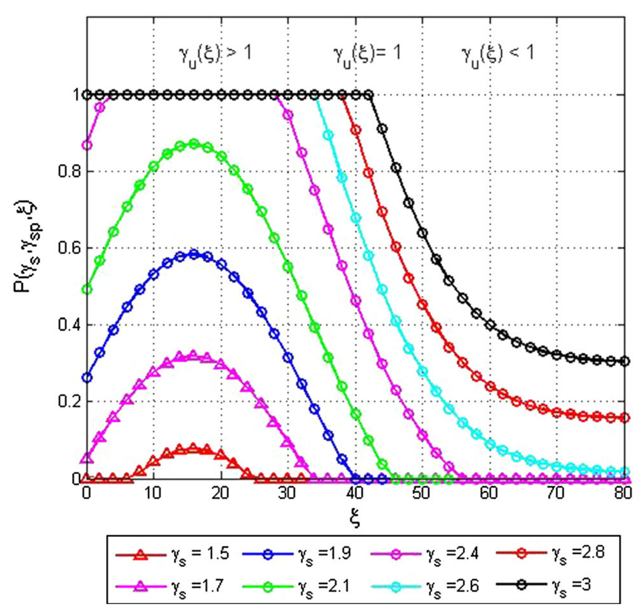

Fig. 4 SU transmit power verses sensing metric ξ for secondary channel variations

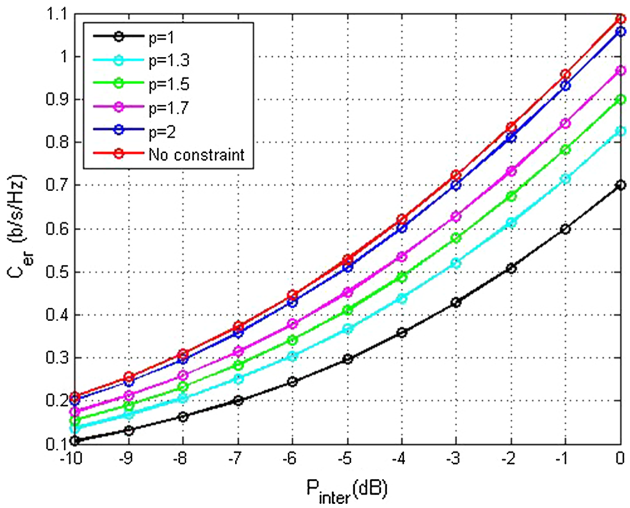

Fig. 5 Capacity verses received interference power constraint for Rayleigh fading Channel

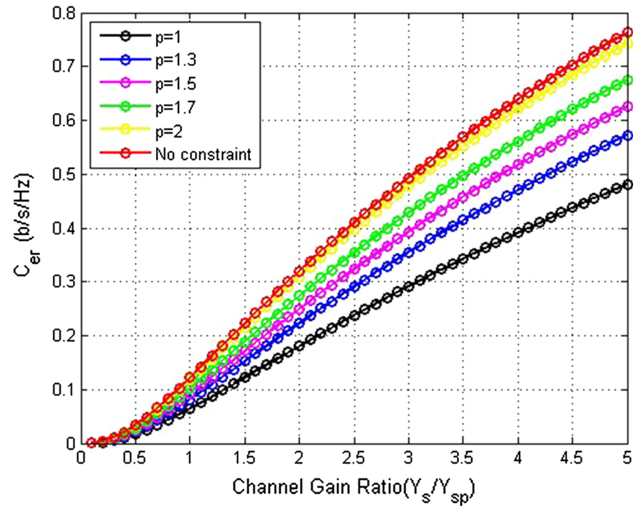

Fig. 7 Capacity verses channel gain ratio under Rayleigh fading for different ρ,$P_{Inter} = -6dB$

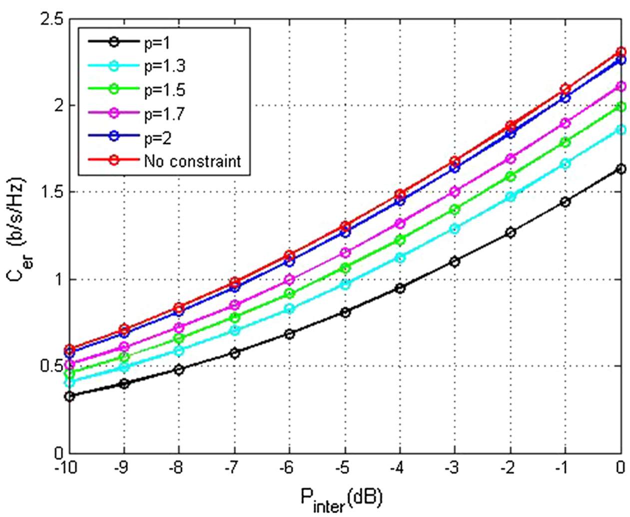

Fig. 6 Capacity verses received interference power constraint for Nakagami-m fading Channel with $m = 2$

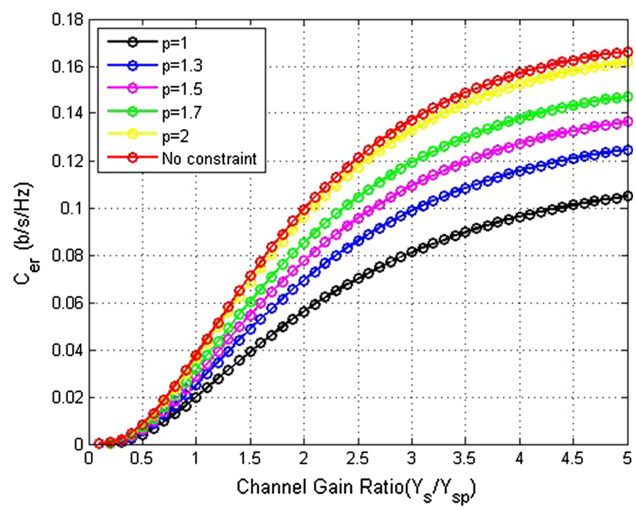

Fig. 8 Capacity verses channel gain ratio under Nakagami-m fading ($m = 2$) for different ρ

$P_{Inter} = -6dB$ for different values of ρ and therefore P_{Peak}. It is observed that for given peak power constraint channel capacity increase with an increase in channel gain ratio. The reason lies in a fact that as the channel between secondary transmitter and primary receiver becomes weak, the secondary user may take advantage from the situation and can transmit at much higher values of the P_{Peak}. while satisfying the average interference equals to $-6dB$, which results into higher channel capacity. Moreover, for the same channel gain ration, channel capacity can be enhanced by increasing peak transmission power up to certain values of ρ. and thereafter it converges towards no peak power constraint. Comparison between Figs. 7 and 8 revealed that capacity for Rayleigh fading channel is more than less severe Nakagami-m fading with $m = 2$. The channel capacity as a function of channel gain ratio and soft sensing information is plotted in Figs. 9 and 10 for Rayleigh and Nakagami-m fading channel respectively while satisfying both spectrum sharing constraint i.e. $P_{Peak} = 0dB$ and $P_{Inter} = -6dB$.

It is observed that secondary user adapt its transmission power and therefore channel capacity in accordance with the soft sensing information pertaining to the primary user activity in channel by transmitting at lower power levels for the higher values of ξ ($Y_u(\xi) < 1$). Where, the probability of primary user being active in a channel is higher (Refer Fig. 4) and at higher power level for samller values of ξ i.e.$Y_u(\xi) > 1$. Futher, it can also be observed that when channel gain ratio is strong due to weak channel power gain between STx and PRx, the channel capacity is higher than weak channel gain ratio and is tightly controlled by the peak transmit power constraint impose on secondary user unlike a scenarion presented in [19] where transmission power and channel capacity is monotonically increasing function of channel gain ratio and is governed by average recived power constraint only.

The channel capacity for less severe Nakagami- m fading with $m = 2$ shown in Fig. 10 reveals that channel capacity under similar environment is less than severe Rayleigh fading case where secondary user adapt its transmission power to transmit emphatically at higher power levels to increase its channel capacity by exploiting channel conditions in its favor.

Figure 11 shows relation between transmission rate, signal interference plus noise ratio and outage probability. It is observed that for given SINR value, transmission rate of primary user increases with an increase in outage probability (δ). Moreover, δ decreases with an increase in SINR to keep transmission rate. In addition to this, to maintain outage constant, transmission rate increases as SINR improves. Another interesting observation is that for lower value of outage interference for secondary user does not deteriorate transmission rate of primary user. The primary transmission rate with and without interference are very comparable for lower values of δ. Whereas, for high values of δ, transmission rate improves with an increase in SINR. The primary user gain better performance,

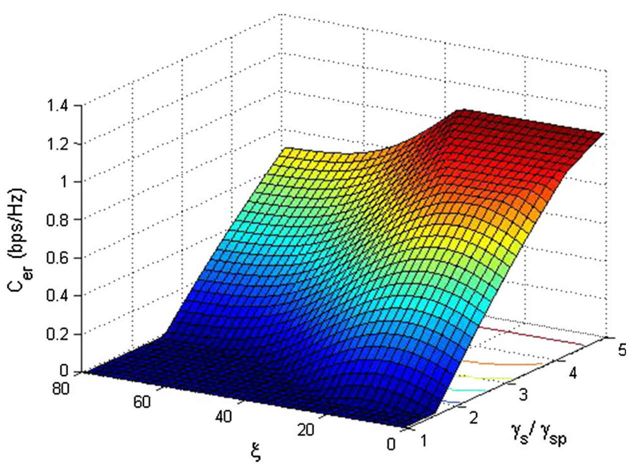

Fig. 9 Channel capacity verses channel gain ratio and ξ for Rayleigh fading channel, with $P_{Peak} = 0dB$, $P_{Inter} = -6dB$, $\gamma_{sp} = 2$ and ξ

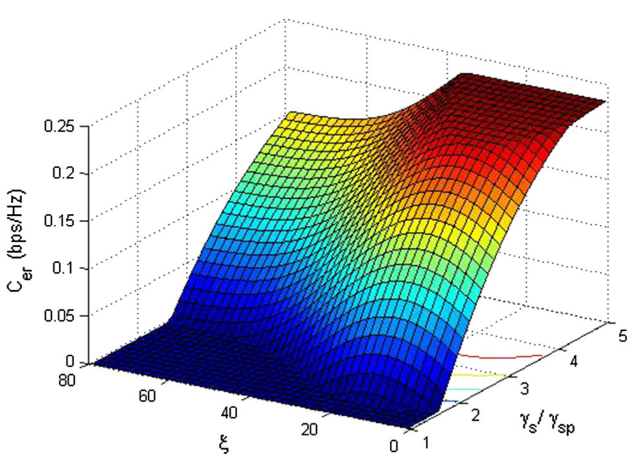

Fig. 10 Channel capacity verses channel gain ratio and ξ for nakagami- m fading channel, with $m = 2$ (Rician), $P_{Peak} = 0dB$, $P_{Inter} = -6dB$, $\gamma_{sp} = 2$ and ξ

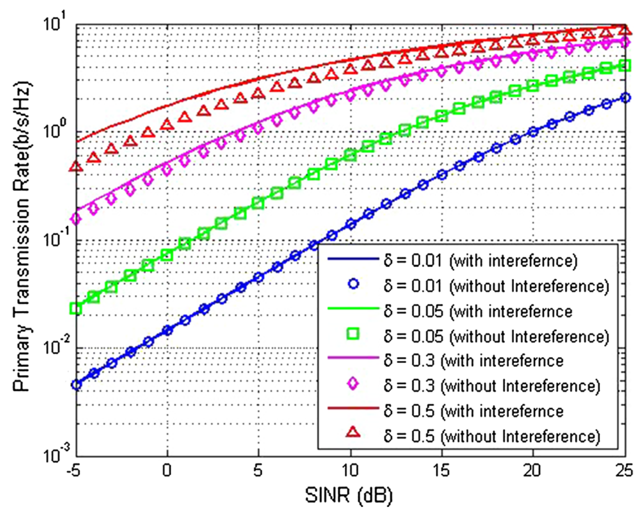

Fig. 11 Impact of cognitive user interference on Primary Transmission Rate for given outage probability

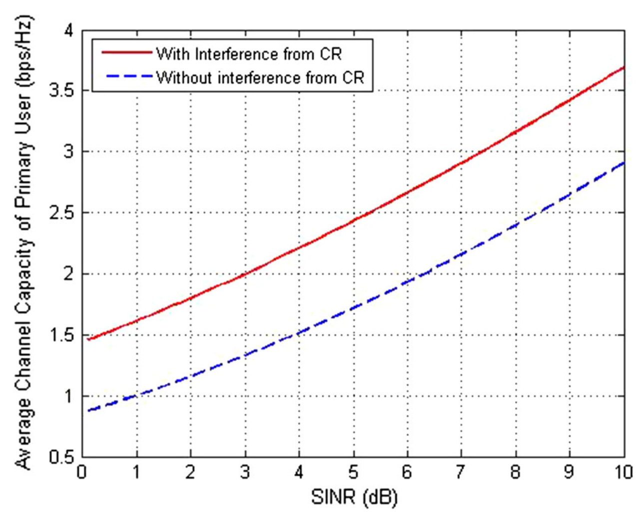

Fig. 12 Impact of cognitive user intereference on average channel capacity of primary user

especially if it experience high values of outage, by sharing same channel with cognitive user.

A comparison of the average channel capacity of the primary user with and without interference from the cognitive user is shown in Fig. 12. It is interesting to note that significant capacity gain can be achieved by primary user if cognitive user is allowed to share channel with primary user such that received interference from cognitive user to primary remains below the predefined received interference constraint. Here, we have considered non- cooperative communication scheme for secondary user. It is expected that the capacity gain for primary user can be improved further if secondary user cooperates with primary user by sharing its transmission power in exchange for using channel.

6 Conclusion

In this paper, we have considered a spectrum sharing system in which secondary user adapt its transmission power by exploiting soft sensing information about primary user activity in shared channel, secondary user's channel state information and fading conditions between secondary and primary user for joint peak transmit power constraint for secondary user and average received interference power costraint for primary receiver. The ergodic channel capacity with power adapatation policy for the spectrum sharing system is illusrated for Rayleigh and Rician fading by varing fading parameter of Nakagami- m fading. The numerically computed results are presented to illustrate that significant capacity gain may be acheived by secondary user by controlling its transmission parameters based on the spectrum sensing information and channel conditions for primary and secondary users. Moreover, it has also been demonstrated that secondary user transmission power and therefore channel capacity for Rayleigh fading is more than Rician fading channel. In addition to this, the impact of cognitive user interference on the performance of primary user is also investiagted. It is shown that the primary user can acheieve significant capacity gain by allowing secondary user to share channel with it such that received interference from cognitive user to primary remains below the predefined received interference constraint.

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