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Rate and Power Optimization Under Received-Power Constraints for Opportunistic Spectrum-Sharing Communication

Indu Bala[1] · Manjit Singh Bhamrah[1] · Ghanshyam Singh[2]

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Abstract In this paper, the channel capacity of secondary user is investigated for opportunistic spectrum sharing with primary user in a Rayleigh fading environment. In the proposed communication scenario, on finding transmission opportunities in licensed band, secondary user utilizes the band as long as the interference power inflicted on primary receiver is below the predefined threshold, and adjusts its transmission power and data rate based on the sensing information available from spectrum sensor. In this context, two different adaptation schemes namely adaptive transmission power scheme and adaptive rate and transmission power scheme are investigated under joint peak and average received power constraints at primary receiver for multilevel quadrature amplitude modulation format. The closed form expressions are derived for the ergodic channel capacities of these schemes and numerical results are presented to validate the theoretical results. Moreover, a comparison between channel capacities is given to illustrate the benefit of using soft sensing information under said constraints.

Keywords Cognitive radio · Spectrum sensing · Spectrum sharing · Peak and received power constraint · Rate and power adaptation schemes · Rayleigh fading channel

1 Introduction

From past few years, the rapid deployment of bandwidth hungry wireless applications in a market has triggered a huge demand for bandwidth and, the same is expected to grow more in future. In traditional spectrum allocation policies, the frequency bands are licensed to the

✉ Indu Bala
i.rana80@gmail.com

1 ECE Department, Punjabi University, Patiala, Punjab, India

2 ECE Department, JUIT Waknaghat, Solan, Himachal Pradesh, India

users for long-term access over a geographical area and therefore, it has become extremely difficult to accommodate upcoming wireless applications in future. On contrary to this, a recent Federal Communication Commission (FCC) report has revealed that most of the allocated spectrum is being used sporadically and therefore the existing spectrum scarcity problem has arisen mainly due to the inefficient usage of spectrum than the physical shortage of the spectrum [1]. To overcome this spectrum scarcity problem, J. Mitola introduced the concept of cognitive radio back in 1999. The technology allows the unlicensed cognitive user, known as secondary user (SU), to constantly monitor its surrounding environment and to adapt its transmission parameters in such a manner that it may coexist with licensed primary users (PUs) over a same channel without exceeding interference limit to the primary user [2]. Different communications paradigms have been proposed for cognitive radio systems such as underlay, overlay and interweave [3]. In underlay communication system, the secondary user is allowed to operate simultaneously with primary user as long as the interference caused to it is below a predefined threshold limit [4–6]. Whereas, in overlay system, the cognitive radios make use of the sophisticated signal processing and coding techniques to maintain or improve the communication of primary users by retransmitting its messages while also obtaining some additional bandwidth for their own communication [7, 8]. In interweave systems; the secondary users opportunistically exploit spectral holes to communicate without disrupting primary user operation [9, 10]. In this paper, interweave approach is considered in which secondary user continuously monitors frequency bands and access a particular band opportunistically such that no or minimum interference experienced by active primary user [3].

In most of the previous studies, the capacity of fading channels is studied under various transmit power constraints, and the corresponding optimal and suboptimal power allocation schemes have been obtained. For example, Khojastepour to investigate the ergodic capacity limit of fading channel under peak and average transmit power constraints [11]. In [12], author has determined the capacity of an additive white Gaussian noise (AWGN) fading channel with an average power constraint under different channel side information (CSI) conditions. Ghasemi and Sousa 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 [13]. Zhang [14] has demonstrated that ergodic capacity of both primary as well as secondary users can be enhanced by considering primary and secondary CSI together. Gastpar introduced received power constraint over transmit power constraint and derived the capacities of different AWGN channels under a received power constraint [15]. The capacities derived in [15], are shown to be quite similar to those under a transmit power constraint because the received power to the transmit power is fixed in an AWGN channel. However, the same is not true for fading channel. Recently, SU channel capacity analysis under received power constraints has grabbed a lot of attention. In [16], the optimum SU transmission strategy is obtained under interference power constraints at primary receivers for multi-antenna SU transmitters, and in [17] for multiple secondary transmitters in a multiple-access channel (MAC). Leila and Sonia have also used secondary CSI and cross-link gain between the secondary transmitter (ST) and primary receiver (PR) to optimize SU transmission power under peak and average received-power at the primary receiver [18]. In most of the previous works, secondary CSI is used to adaptively adjust the transmission power [13–18] and few have used primary CSI to adapt SU transmission power [14]. However, from a practical point of view, it is difficult for a SU to have direct access to the CSI pertaining to the PU link, and therefore few recent studies are based on the sensing of a primary user activity at the SU side for opportunistic spectrum sharing. In this context, soft sensing information is acquired by mounting a sensing detector on secondary equipment that periodically scan frequency band(s) to know the presence or absence of a primary user. Using soft-sensing information with no prior knowledge about SU CSI at secondary transmitter, a power control scheme is developed to maximize the SU channel capacity in [19]. In [20], the ergodic channel capacity of secondary user using soft sensing information and secondary CSI is investigated under peak transmit power and average interference power constraint. Generally, energy detection scheme is used to obtain this soft sensing information due to ease in implementation and low computational complexities [21, 22].

In this paper, an opportunistic spectrum sharing communication system is considered, where the secondary user control its transmission power using soft sensing statistics under joint peak and average received power constraints. Since, the cognitive radio is adaptive to the fading environment and may change its transmit power, data rate and modulation scheme based on sensing data, different rate and power adaptation policies can be established [23]. Therefore, the ergodic channel capacity is also investigated for adaptive transmission power and adaptive rate and transmission power M-QAM t policy under joint peak and average received power constraint. The work differs from previous work in that soft sensing information is used to optimize transmission power and data rate under joint peak and average receive power constraints at primary receiver for Rayleigh fading channel. The rest of the paper is organized as follows: the spectrum sharing system model is introduced in section II. The closed form expression for the ergodic capacity of secondary user under adaptive transmission power scheme and adaptive rate and transmission power M-QAM scheme is derived in section III and section IV respectively. Finally, numerically computed results and discussion followed by conclusion are given in section IV and V respectively.

2 System Model

Consider an opportunistic spectrum sharing communication system having one primary transmitter (PTx) that uses its allocated licensed wireless channel to transmit information to the primary receiver (PRx) as shown in Fig. 1. At the same time, to achieve higher spectral efficiency, a secondary unlicensed user, known as cognitive user, is allowed to initiate a new session by sharing a licensed wireless channel of primary, provided interference experienced by it is below predefined threshold value. It is assumed that primary transmitter uses a Gaussian codebook with an average transmit power equals to P_t and the link between PTx and PRx is stationary block fading channel with coherence time T_c. The block fading channel is one in which the channel gain remains constant for coherence time T_c and attains new independent value after that. This implies that the primary user activity attains a new independent value (ON/OFF) after every T_c time [24].

The channel between STx and SRx is assumed discrete time flat fading channel with perfect channel state information (CSI) available with STx and SRx pair in advance. The channel gain is $\sqrt{\gamma_s}$ between STx and SRx, $\sqrt{\gamma_p}$ between PTx and PRx, $\sqrt{\gamma_m}$ between PTx and STx and $\sqrt{\gamma_{sp}}$ between STx and PRx. All these channel power gains are independent and vary according to their distributions. It is assumed 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 γ_s whereas for γ_m and γ_{sp}, Rayleigh distribution is assumed with variances depend on the physical separation between associated nodes for

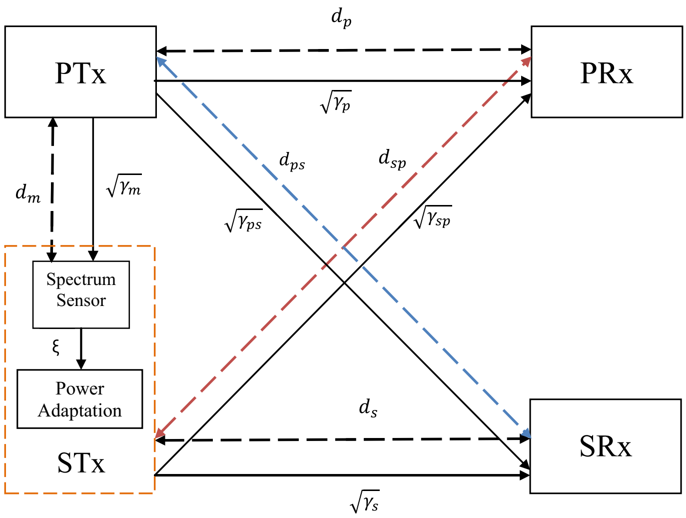


Fig. 1 Opportunistic spectrum sharing secondary communication system

example d_m^{-2} for γ_m, d_{sp}^{-2} for γ_{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.

As shown in Fig. 1, in proposed secondary communication system, 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 primary user, it calculates a sensing metric ξ. Since, it follows stationary block fading model, one may consider PU active in licensed band with probability α or inactive with probability $\bar{\alpha} = 1 - \alpha$ for T_c time duration. These test statics are used to estimate the primary user's activity in ON or OFF state. The parameter ξ can be modeled according to the Chi-square probability distribution functions (PDFs) with ν degree of freedom that depends on the number of samples used in the sensing duration N_s. According to [25, 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 in ON or OFF state, the PDFs of ξ are defined as $f_{on}(\xi) \sim N\left(\mu_{on}, \delta_{on}^2\right)$ and $f_{off}(\xi) \sim N\left(\mu_{off}, \delta_{off}^2\right)$ respectively and given by [19]

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

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

The probability distributions of $f_{on}(\xi)_{PU\_Active}$ and $f_{off}(\xi)_{PU\_Inactive}$ will be given by

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

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

The secondary transmitter adapts its transmission power using sensing statistics $f_{off}(\xi)$ and $f_{on}(\xi)$ while satisfying the predefined power constraints. Given that secondary transmission should not affect the QoS at primary receiver, the constraints on average and peak received power are imposed when primary user is ON. These constraints are defined as

$$E_{\gamma_s,\gamma_{sp},\xi}\{P(\gamma_s, \gamma_{sp}, \xi)\gamma_{sp}\}_{PU\_On} \le P_{Avg} \tag{5}$$

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

where (3) and (4) represents average and peak received power constraints at primary receiver respectively. $P(\gamma_s, \gamma_{sp}, \xi)$ represents SU transmit power, and $E_{\gamma_s,\gamma_{sp},\xi}[.]$ defines expectation over joint probability density function of γ_s, γ_{sp} and ξ.

3 Adaptive Transmission Power Scheme

In this section, power adaptation scheme is investigated for Rayleigh fading channel under joint peak and average received power constraints at primary receiver as given in (5) and (6) and the benefits of soft sensing information are analyzed for proposed opportunistic spectrum sharing communication system.

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 [26]. In [18], ergodic capacity for Rayleigh fading channel is investigated under peak and average received power constraints at primary receiver without using soft sensing information regarding PU activity. In this paper, secondary CSI and soft sensing information about PU activity is used to optimize channel capacity under joint average (5) and peak received power (6) constraints at primary receiver. Adopting the similar approach that used in [18, 19], the ergodic channel capacity that achieve optimum power control such that both the received power constraints are satisfied, represents the solution to the following optimization problem:

$$\frac{C_{er}}{B} = \max_{P(\gamma_s,\gamma_{sp},\xi)} E_{\gamma_s,\gamma_p,\xi}\left\{log_2\left(1 + \frac{P(\gamma_s, \gamma_{sp}, \xi)\gamma_s}{N_0 B}\right)\right\} \tag{7}$$

s.t

$$E_{\gamma_s,\gamma_{sp},\xi}\{P(\gamma_s, \gamma_{sp}, \xi)\gamma_{sp}\}_{PU\_on} \le P_{Avg} \tag{8}$$

$$\{P(\gamma_s, \gamma_{sp}, \xi)\gamma_{sp}\}_{PU\_on} \le P_{Peak}; \quad \forall \gamma_s, \gamma_{sp} \quad \text{and} \quad \xi \tag{9}$$

Using sensing statistics (7) may be written as

$$\frac{C_{er}}{B} = E_{\gamma_s,\gamma_{sp},\xi/PU\_off}\left\{log_2\left(1+\frac{P(\gamma_s,\gamma_{sp},\xi)\gamma_s}{N_0B}\right)\right\}\bar{\alpha} + E_{\gamma_s,\gamma_{sp},\xi/PU\_on}\left\{log_2\left(1+\frac{P(\gamma_s,\gamma_{sp},\xi)\gamma_s}{N_0B}\right)\right\}\alpha \tag{10}$$

To maximize the capacity function of (10), Lagrangian equation may be written as

$$\begin{aligned} L_{C_{er}} &= \left[P(\gamma_s,\gamma_{sp},\xi),\lambda_1,\lambda_2(\gamma_s,\gamma_{sp},\xi),\lambda_3(\gamma_s,\gamma_{sp},\xi)\right] \\ &= \bar{\alpha}E_{\gamma_s,\gamma_{sp},\xi/PU\_off}\left\{log_2\left(1+\frac{P(\gamma_s,\gamma_{sp},\xi)\gamma_s}{N_0B}\right)\right\} \\ &\quad + \alpha E_{\gamma_s,\gamma_{sp},\xi/PU\_on}\left\{log_2\left(1+\frac{P(\gamma_s,\gamma_{sp},\xi)\gamma_s}{N_0B}\right)\right\} \\ &\quad - \lambda_1\left[E_{\gamma_s,\gamma_{sp},\xi/PU\_on}\left(P(\gamma_s,\gamma_{sp},\xi)\gamma_{sp} - P_{Avg}\right)\right] \\ &\quad + \int_0^\infty\int_0^\infty\int_0^\infty \lambda_2(\gamma_s,\gamma_{sp},\xi)P(\gamma_s,\gamma_{sp},\xi)\gamma_{sp}d\gamma_s d\gamma_{sp}d\xi \\ &\quad - \int_0^\infty\int_0^\infty\int_0^\infty \lambda_2(\gamma_s,\gamma_{sp},\xi)\left[\{P(\gamma_s,\gamma_{sp},\xi)\gamma_{sp}\}_{PU\_on} - P_{Peak}\right]d\gamma_s d\gamma_{sp}d\xi \end{aligned} \tag{11}$$

Taking derivative w.r.t $P(\gamma_s,\gamma_{sp},\xi)$ and equating to zero, (11) will become

$$\begin{aligned} &\bar{\alpha}f_{off}(\xi)\frac{\frac{\gamma_s}{N_0B}}{1+\left(\frac{P(\gamma_s,\gamma_{sp},\xi)\gamma_s}{N_0B}\right)} + \alpha f_{on}(\xi)\frac{\frac{\gamma_s}{N_0B}}{1+\left(\frac{P(\gamma_s,\gamma_{sp},\xi)\gamma_s}{N_0B}\right)} - \lambda_1 f_{on}(\xi)\gamma_{sp} + \lambda_2(\gamma_s,\gamma_{sp},\xi) \\ &- \lambda_3(\gamma_s,\gamma_{sp},\xi)\gamma_{sp} = 0 \end{aligned} \tag{12}$$

$$\begin{aligned} &\bar{\alpha}f_{off}(\xi)\left(\frac{\gamma_s}{P(\gamma_s,\gamma_{sp},\xi)\gamma_s+N_0B}\right) + \alpha f_{on}(\xi)\left(\frac{\gamma_s}{P(\gamma_s,\gamma_{sp},\xi)\gamma_s+N_0B}\right) \\ &\quad - \lambda_1 f_{on}(\xi)\gamma_{sp} + \lambda_2(\gamma_s,\gamma_{sp},\xi) - \lambda_3(\gamma_s,\gamma_{sp},\xi)\gamma_{sp} = 0 \\ &\left(\bar{\alpha}f_{off}(\xi) + \alpha f_{on}(\xi)\right)\left(\frac{\gamma_s}{P(\gamma_s,\gamma_{sp},\xi)\gamma_s+N_0B}\right) \\ &\quad - \lambda_1 f_{on}(\xi)\gamma_{sp} + \lambda_2(\gamma_s,\gamma_{sp},\xi) - \lambda_3(\gamma_s,\gamma_{sp},\xi)\gamma_{sp} = 0 \end{aligned} \tag{13}$$

Because, the objective function is concave in $P(\gamma_s,\gamma_{sp},\xi)$; the KKT conditions are necessary and sufficient for optimality and are given below

$$\lambda_1\left(E_{\gamma_s,\gamma_{sp},\xi/PU\_On}\left(\left(P(\gamma_s,\gamma_{sp},\xi)\gamma_{sp}\right)_{PU\_On} - P_{Avg}\right)\right) = 0 \tag{14}$$

$$\lambda_2(\gamma_s,\gamma_{sp},\xi)P(\gamma_s,\gamma_{sp},\xi) = 0 \tag{15}$$

$$\lambda_3(\gamma_s,\gamma_{sp},\xi)\left(\left(\left(P(\gamma_s,\gamma_{sp},\xi)\gamma_{sp}\right)_{PU\_On} - P_{Peak}\right)\right) = 0 \tag{16}$$

Case I Suppose $P^*(\gamma_s, \gamma_{sp}, \xi) = 0$ for some values of γ_s, γ_{sp} and ξ. It requires $\lambda_3(\gamma_s, \gamma_{sp}, \xi) = 0$ in (16) and $\lambda_2(\gamma_s, \gamma_{sp}, \xi) \geq 0$ in (15). Substituting these conditions in (13), we have

$$\left(\bar{\alpha} f_{off}(\xi) + \alpha f_{on}(\xi)\right)\left(\frac{\gamma_s}{N_0 B}\right) - \lambda_1 f_{on}(\xi)\gamma_{sp} \leq 0 \tag{17}$$

$$\begin{aligned} &\left(\alpha + \bar{\alpha}\frac{f_{off}(\xi)}{f_{on}(\xi)}\right)\left(\frac{\gamma_s}{N_0 B}\right) - \lambda_1 \gamma_{sp} \leq 0 \\ &\gamma_u(\xi)\frac{\gamma_s}{N_0 B} \leq \lambda_1 \gamma_{sp} \\ &\frac{\gamma_u(\xi)}{\lambda_1 N_0 B} \leq \frac{\gamma_{sp}}{\gamma_s} \end{aligned} \tag{18}$$

where

$$\alpha + \bar{\alpha}\frac{f_{off}(\xi)}{f_{on}(\xi)} = \gamma_u(\xi) \tag{19}$$

Case II Suppose $P^*(\gamma_s, \gamma_{sp}, \xi) = \frac{P_{Peak}}{\gamma_{sp}}$ for some values of γ_s, γ_{sp} and ξ. It requires $\lambda_2(\gamma_s, \gamma_{sp}, \xi) = 0$ in (15) and $\lambda_3(\gamma_s, \gamma_{sp}, \xi) \geq 0$ in (16). Substituting these conditions in (13), we have

$$\gamma_u(\xi)\left(\frac{\gamma_s}{\frac{P_{Peak}\gamma_s}{\gamma_{sp}} N_0 B}\right) - \lambda_1 \gamma_{sp} \geq 0 \tag{20}$$

$$\begin{aligned} &\gamma_u(\xi)\left(\frac{\gamma_s}{P_{Peak}\frac{\gamma_s}{\gamma_{sp}} + N_0 B}\right) \geq \lambda_1 \gamma_{sp} \\ &\left(\frac{\gamma_u(\xi)}{\lambda_1} - P_{Peak}\right)\gamma_s \geq N_0 B \gamma_{sp} \\ &\frac{\gamma_v(\xi)}{N_0 B} \geq \frac{\gamma_{sp}}{\gamma_s} \end{aligned} \tag{21}$$

where

$$\frac{\gamma_u(\xi)}{\lambda_1} - P_{Peak} = \gamma_v(\xi) \tag{22}$$

Case III $0 \leq P^*(\gamma_s, \gamma_{sp}, \xi) = \frac{P_{Peak}}{\gamma_{sp}}$ for some values of γ_s, γ_{sp} and ξ. It requires $\lambda_2(\gamma_s, \gamma_{sp}, \xi) = \lambda_2(\gamma_s, \gamma_{sp}, \xi) = 0$ in (15) and (16). Substituting these conditions in (13), we have

$$\begin{aligned} &\gamma_u(\xi)\left(\frac{\gamma_s}{P(\gamma_s, \gamma_{sp}, \xi)\gamma_s + N_0 B}\right) - \lambda_1 \gamma_{sp} = 0 \\ &\frac{\gamma_u(\xi)}{P(\gamma_s, \gamma_{sp}, \xi) + \frac{N_0 B}{\gamma_s}} = \lambda_1 \gamma_{sp} \\ &\frac{\gamma_u(\xi)}{\lambda_1 \gamma_{sp}} - \frac{N_0 B}{\gamma_s} = P(\gamma_s, \gamma_{sp}, \xi) \end{aligned} \tag{23}$$

Thus, the optimum adaptive transmission power control scheme under received peak and average received power constraints at primary receiver will be given by

$$P(\gamma_s, \gamma_{sp}, \xi) = \begin{pmatrix} \frac{P_{Peak}}{\gamma_{sp}} & \frac{\gamma_v(\xi)}{N_0 B} \geq \frac{\gamma_{sp}}{\gamma_s} \\ \frac{\gamma_u(\xi)}{\lambda_1 \gamma_{sp}} - \frac{N_0 B}{\gamma_s} & \frac{\gamma_v(\xi)}{N_0 B} \leq \frac{\gamma_{sp}}{\gamma_s} \leq \frac{\gamma_u(\xi)}{\lambda_1 N_0 B} \\ 0 & \frac{\gamma_u(\xi)}{\lambda_1 N_0 B} \leq \frac{\gamma_{sp}}{\gamma_s} \end{pmatrix} \tag{24}$$

The adaptive transmission power scheme implies that the transmission is suspended when the link between secondary transmitter and receiver is weak as compared to the γ_{sp}. As the ratio $\frac{\gamma_{sp}}{\gamma_s}$ decreases, the secondary user exploits the weak link between primary transmitter and receiver and start transmitting at higher power levels. The latter, however, is limited to $\frac{P_{Peak}}{\gamma_{sp}}$; to satisfy the peak received power constraint at primary receiver. The value of Lagrangian parameter λ_1 can be calculated by putting $P(\gamma_s, \gamma_{sp}, \xi)$ given in (24) in (8) and using equality given in (22); thus yielding

$$\begin{aligned} P_{Avg} = & \iiint_{\frac{\gamma_{sp}}{\gamma_s} \leq \frac{\frac{\gamma_u(\xi)}{\lambda_1} - P_{Peak}}{N_0 B}} P_{Peak} f_{\gamma_s}(\gamma_s) f_{\gamma_{sp}}(\gamma_{sp}) f_{on}(\xi) d\gamma_s d\gamma_{sp} d\xi \\ & + \iiint_{\frac{\frac{\gamma_u(\xi)}{\lambda_1} - P_{Peak}}{N_0 B} \leq \frac{\gamma_{sp}}{\gamma_s} \leq \frac{\gamma_u(\xi)}{\lambda_1 N_0 B}} \left(\frac{\gamma_u(\xi)}{\lambda_1} - N_0 B \frac{\gamma_{sp}}{\gamma_s} \right) f_{\gamma_s}(\gamma_s) f_{\gamma_{sp}}(\gamma_{sp}) f_{on}(\xi) d\gamma_s d\gamma_{sp} d\xi \end{aligned} \tag{25}$$

where $f_x(x)$ represents PDF of random variable x. Since, integration in (25) depends on random variable $\frac{\gamma_{sp}}{\gamma_s}$; we define a random variable $v = \frac{\gamma_{sp}}{\gamma_s}$, then, the distribution of random variable v is given by

$$f_v(v) = \frac{1}{(v+1)^2} \tag{26}$$

Putting (26) into (25), it will become

$$P_{Avg} = \left[\int_0^{\frac{\gamma_{sp}}{\gamma_s} \leq \frac{\frac{\gamma_u(\xi)}{\lambda_1} - P_{Peak}}{N_0 B}} \frac{P_{Peak}}{(v+1)^2} dv + \int_{\frac{\frac{\gamma_u(\xi)}{\lambda_1} - P_{Peak}}{N_0 B}}^{\frac{\gamma_u(\xi)}{\lambda_1 N_0 B}} \frac{\left(\frac{\gamma_u(\xi)}{\lambda_1} - N_0 B v \right)}{(v+1)^2} dv \right] \times \int_{P_1(\gamma_u(\xi))}^{P_2(\gamma_u(\xi))} f_{on}(\xi) d\xi \tag{27}$$

After simplification, (27) becomes

$$P_{Avg} = \left[P_{Peak} + N_0 B \log \left(1 - \frac{\lambda_1 P_{Peak}}{\gamma_u(\xi) + \lambda_1 N_0 B} \right) \right] \times \int_{P_1(\gamma_u(\xi))}^{P_2(\gamma_u(\xi))} f_{on}(\xi) d\xi \tag{28}$$

Let us assume

$$\int_{P_1(\gamma_u(\xi))}^{P_2(\gamma_u(\xi))} f_{on}(\xi)d\xi = X = \frac{1}{\sqrt{4\pi}}\left[\Gamma\left(\frac{1}{2},\frac{(P_1(\gamma_u(\xi))-\mu_{on})^2}{2\delta_{on}^2}\right)-\Gamma\left(\frac{1}{2},\frac{(P_2(\gamma_u(\xi))-\mu_{on})^2}{2\delta_{on}^2}\right)\right] \tag{29}$$

where $\Gamma(a,b)=\int_b^\infty t^{a-1}e^{-t}dt$ is the incomplete Gamma function [27, Eq. 8.35.1] and $P_1(\gamma_u(\xi))$ and $P_2(\gamma_u(\xi))$ are the roots for $\alpha+\bar{\alpha}\frac{f_{off}(\xi)}{f_{on}(\xi)}=\gamma_u(\xi)$. More details on how (29) is derived are given in Appendix and on simplification, (28) yields λ_1 as

$$\lambda_1 = \frac{\gamma_u(\xi)\left(1-\exp\left(\frac{\left(\frac{P_{Avg}}{X}-P_{Peak}\right)}{N_0B}\right)\right)}{P_{Peak}-N_0B\left(1-\exp\left(\frac{\left(\frac{P_{Avg}}{X}-P_{Peak}\right)}{N_0B}\right)\right)} \tag{30}$$

Now, putting (24) into (10), the ergodic channel capacity of secondary user can be calculated as follows

$$\begin{aligned}\frac{C_{er}}{B} = &\iiint_{\frac{\lambda_1N_0B}{\gamma_u(\xi)}\le\frac{\gamma_s}{\gamma_{sp}}\le\frac{N_0B}{\gamma_v(\xi)}} log_2\left(\left(1+\frac{\gamma_u(\xi)}{\lambda_1\gamma_{sp}}-\frac{N_0B}{\gamma_s}\right)\frac{\gamma_s}{N_0B}\right)f_{\gamma_s}(\gamma_s)f_{\gamma_{sp}}(\gamma_{sp})f_{on}(\xi)d\gamma_s d\gamma_{sp}d\xi \\ &+\iiint_{\frac{\gamma_s}{\gamma_{sp}}\ge\frac{N_0B}{\gamma_v(\xi)}} log_2\left(1+\frac{P_{Peak}\gamma_s}{N_0B\gamma_{sp}}\right)f_{\gamma_s}(\gamma_s)f_{\gamma_{sp}}(\gamma_{sp})f_{on}(\xi)d\gamma_s d\gamma_{sp}d\xi\end{aligned} \tag{31}$$

$$\frac{C_{er}}{B} = \left[\int_{\frac{\lambda_1N_0B}{\gamma_u(\xi)}}^{\frac{N_0B}{\gamma_v(\xi)}} log_2\left(\frac{\gamma_u(\xi)v}{\lambda_1N_0B}\right)f_v(v)f_{on}(\xi)dvd\xi + \int_{\frac{N_0B}{\gamma_v(\xi)}}^{\infty} log_2\left(1+\frac{P_{Peak}v}{N_0B}\right)f_v(v)f_{on}(\xi)dvd\xi\right]$$

Using (26), (31) becomes

$$\frac{C_{er}}{B} = \left[\int_{\frac{\lambda_1N_0B}{\gamma_u(\xi)}}^{\frac{N_0B}{\gamma_v(\xi)}} log_2\frac{1}{(v+1)^2}dv + \int_{\frac{N_0B}{\gamma_v(\xi)}}^{\infty} log_2\left(1+\frac{P_{Peak}v}{N_0B}\right)\frac{1}{(v+1)^2}dv\right]\times\int_{P_1(\gamma_u(\xi))}^{P_2(\gamma_u(\xi))} f_{on}(\xi)d\xi$$

where $v=\frac{\gamma_s}{\gamma_{sp}}$. After simple mathematical calculations and using (30), the closed form expression for ergodic channel capacity will be given by

$$\begin{aligned}\frac{C_{er}}{B} = &\frac{1}{\sqrt{4\pi}}\left[\Gamma\left(\frac{1}{2},\frac{(P_1(\gamma_u(\xi))-\mu_{on})^2}{2\delta_{on}^2}\right)-\Gamma\left(\frac{1}{2},\frac{(P_2(\gamma_u(\xi))-\mu_{on})^2}{2\delta_{on}^2}\right)\right] \\ &\times\left[-log_2\left(1-\frac{P_{Peak}\lambda_1}{N_0B\lambda_1+\gamma_u(\xi)}\right)+\frac{P_{Peak}}{P_{Peak}+N_0B}log_2\left(\frac{P_{Peak}\lambda_1}{N_0B\gamma_u(\xi)}\left(N_0B+\frac{\gamma_u(\xi)}{\lambda_1}-P_{Peak}\right)\right)\right]\end{aligned} \tag{32}$$

4 Adaptive Rate and Transmission Power M-QAM Scheme

Adaptive rate and transmission power scheme is used to maximize spectral efficiency for opportunistic spectrum sharing secondary communication system [23]. In this potential scheme symbol duration [28] or constellation size [29] is varied to achieve high spectral efficiency. In this section, ergodic channel capacity of SU is investigated for adaptive data rate and transmission power scheme for given bit error rate under joint peak and average received power constraints. The benefits of soft sensing information and prior knowledge about SU CSI at STx are investigated on the capacity for *Adaptive Rate and Transmission Power* scheme in Multilevel Quadrature Amplitude Modulation (M-QAM) signal constellation. The bit error rate (BER) bound for different values of γ_s, γ_{sp} and ξ for M-QAM when $M \geq 4$ can be expressed as follows [23]

$$BER\left(\gamma_s, \gamma_{sp}, \xi\right) \leq 0.2\exp\left(\frac{-1.5}{M-1}\frac{P\left(\gamma_s, \gamma_{sp}, \xi\right)\gamma_s}{N_0 B}\right) \tag{33}$$

where $BER\left(\gamma_s, \gamma_{sp}, \xi\right)$ is instantaneous BER and M denotes constellation size. After some mathematical manipulations, for given BER requirements, the maximum constellation size can be obtained as follows

$$M\left(\gamma_s, \gamma_{sp}, \xi\right) = 1 + C\frac{P\left(\gamma_s, \gamma_{sp}, \xi\right)\gamma_s}{N_0 B} = 2^{N_b} = 2^{log_2\left(1+C\frac{P\left(\gamma_s, \gamma_{sp}, \xi\right)\gamma_s}{N_0 B}\right)} \tag{34}$$

where

$$C = \frac{-1.5}{ln(5BER)} \leq 1 \tag{35}$$

is a constant and set according to the quality of service (QoS) requirements of opportunistic secondary communication system and N_b is number of bits per symbol. Therefore, the ergodic channel capacity for opportunistic spectrum sharing system operating under joint peak and average received power constraints at PRx and for given BER will become the solution of following Lagrangian optimization problem:

$$\frac{C_{er}(BER)}{B} = \max_{\gamma_s, \gamma_{sp}, \xi}\left\{E_{\gamma_s, \gamma_{sp}, \xi}\left[log_2\left(1 + C\frac{P\left(\gamma_s, \gamma_{sp}, \xi\right)\gamma_s}{N_0 B}\right)\right]\right\} \tag{36}$$

subject to (8) and (9), and

$$0.2exp\left(\left(\frac{-1.5}{M-1}\frac{P\left(\gamma_s, \gamma_{sp}, \xi\right)\gamma_s}{N_0 B}\right)\right) \geq BER \tag{37}$$

Using same approach as presented in Sect. 3, adaptive rate and adaptive transmission power scheme that maximize the ergodic channel capacity for given BER requirements can be formulated as

$$P(\gamma_s, \gamma_{sp}, \xi) = \begin{pmatrix} \frac{P_{Peak}}{\gamma_{sp}} & \frac{C\gamma_v(\xi)}{N_0B} \geq \frac{\gamma_{sp}}{\gamma_s} \\ \frac{\gamma_u(\xi)}{\lambda_1\gamma_{sp}} - \frac{N_0B}{C\gamma_s} & \frac{C\gamma_v(\xi)}{N_0B} \leq \frac{\gamma_{sp}}{\gamma_s} \leq \frac{C\gamma_u(\xi)}{\lambda_1N_0B} \\ 0 & \frac{C\gamma_u(\xi)}{\lambda_1N_0B} \leq \frac{\gamma_{sp}}{\gamma_s} \end{pmatrix} \tag{38}$$

where λ_1 is Lagrangian multiplier and can be calculated such that average received power constraint in (8), is satisfied. Comparing power control scheme presented in (24) with (39), it can be observed that parameter C results into significant power loss in M-QAM adaptation scheme however, this power degradation is independent to the γ_s, γ_{sp} and soft sensing information ξ. Thus, for given BER, ergodic capacity for Adaptive Rate and Transmission Power M-QAM scheme will be given by

$$\begin{aligned}\frac{C_{er}}{B}=&\iiint_{\frac{\lambda_1N_0B}{C\gamma_u(\xi)}\leq\frac{\gamma_s}{\gamma_{sp}}\leq\frac{N_0B}{C\gamma_v(\xi)}} log_2\left(\left(1+C\left(\frac{\gamma_u(\xi)}{\lambda_1\gamma_{sp}}-\frac{N_0B}{C\gamma_s}\right)\right)\frac{\gamma_s}{N_0B}\right)f_{\gamma_s}(\gamma_s)f_{\gamma_{sp}}(\gamma_{sp})f_{on}(\xi)d\gamma_sd\gamma_{sp}d\xi \\ &+\iiint_{\frac{\gamma_s}{\gamma_{sp}}\geq\frac{N_0B}{C\gamma_v(\xi)}} log_2\left(1+\frac{CP_{Peak}\gamma_s}{N_0B\gamma_{sp}}\right)f_{\gamma_s}(\gamma_s)f_{\gamma_{sp}}(\gamma_{sp})f_{on}(\xi)d\gamma_sd\gamma_{sp}d\xi\end{aligned} \tag{39}$$

Using (26), (39) become

$$\begin{aligned}\frac{C_{er}}{B} =& \left[\int_{\frac{\lambda_1N_0B}{C\gamma_u(\xi)}}^{\frac{N_0B}{C\gamma_v(\xi)}} log_2\left(\frac{C\gamma_u(\xi)v}{\lambda_1N_0B}\right)\frac{1}{(v+1)^2}dv + \int_{\frac{N_0B}{C\gamma_v(\xi)}}^{\infty} log_2\left(1+\frac{CP_{Peak}v}{N_0B}\right)\frac{1}{(v+1)^2}dv\right] \\ &\times \int_{P_1(\gamma_u(\xi))}^{P_2(\gamma_u(\xi))} f_{on}(\xi)d\xi\end{aligned}$$

where $v = \frac{\gamma_s}{\gamma_{sp}}$. After simple mathematical manipulations and using (30), the closed form expression for ergodic channel capacity becomes

$$\begin{aligned}\frac{C_{er}}{B} =& \frac{1}{\sqrt{4\pi}}\left[\Gamma\left(\frac{1}{2},\frac{(P_1(\gamma_u(\xi))-\mu_{on})^2}{2\delta_{on}^2}\right) - \Gamma\left(\frac{1}{2},\frac{(P_2(\gamma_u(\xi))-\mu_{on})^2}{2\delta_{on}^2}\right)\right] \\ &\times\left[-log_2\left(1-\frac{CP_{Peak}\lambda_1}{N_0B\lambda_1+C\gamma_u(\xi)}\right)+\frac{CP_{Peak}}{CP_{Peak}+N_0B}log_2\right. \\ &\left.\times\left(\frac{CP_{Peak}\lambda_1}{N_0BC\gamma_u(\xi)}\left(N_0B+\frac{C\gamma_u(\xi)}{\lambda_1}-CP_{Peak}\right)\right)\right]\end{aligned} \tag{40}$$

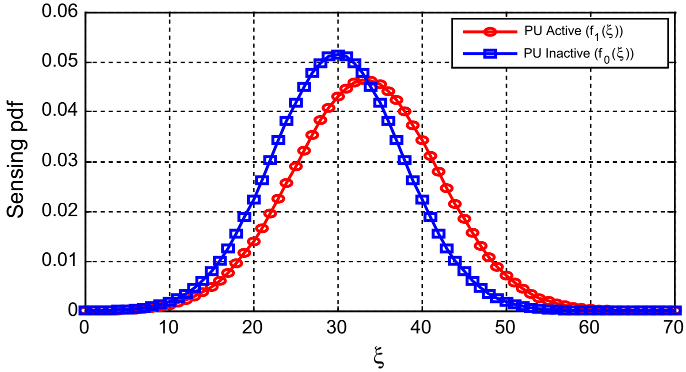
5 Results and Discussions

In this section, both adaptive transmission power and adaptive rate and transmission power are illustrated numerically for opportunistic spectrum sharing system, operating under joint peak and average received interference power constrains. The secondary channel variations are approximated through Rayleigh PDF with unit mean due to multipath propagation between secondary transmitter and receiver.

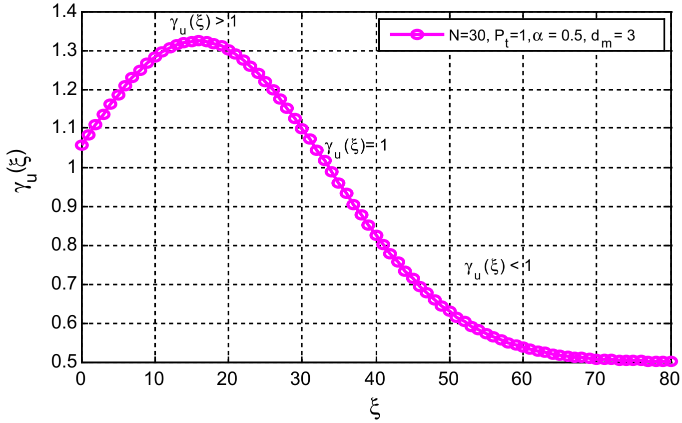
As shown in Fig. 1, it has been assumed that nodes are placed in such a manner that $d_s = d_p = 1$, $d_m = 3$ and $N_0B = 1$. Energy detector is used with number of observation samples (N_s) equals to 30. The PU transmission power P_t is set to 1. It is assumed that PU remains active for 50% of the time with $\alpha = 0.5$. Based on these system parameters, the sensing PDFs of $f_0(\xi)$ and $f_1(\xi)$ and parameter $\gamma_u(\xi) = \alpha + \bar{\alpha}\frac{f_{off}(\xi)}{f_{on}(\xi)}$ as a function of sensing parameter ξ is plotted in Fig. 2a, b respectively.

5.1 Ergodic Capacity for Adaptive Transmission Power Scheme

In Fig. 3, instantaneous secondary transmission power is plotted as presented in (24), for a system operating under different average received power constraints and peak received power constraint approximately equals to 0 dB. For adaptive transmission power scheme, the power variations are shown for three regions: $\gamma_u(\xi) > 1$, $\gamma_u(\xi) = 1$ and $\gamma_u(\xi) > 1$. The value $\gamma_u(\xi) > 1$ represents a scenario where the probability that the primary user is inactive



(a)



(b)

Fig. 2 **a** Sensing PDFs $f_0(\xi)$ and $f_1(\xi)$, **b** $\gamma_u(\xi)$ variation [22]

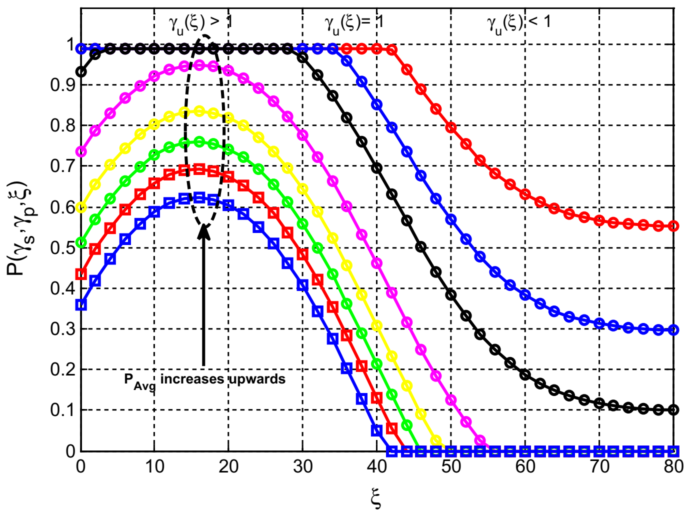


Fig. 3 Instantaneous transmission power with $P_{Peak} \cong 0$ dB verses sensing metric ξ

in a shared channel is higher than being active and, otherwise, by $\gamma_u(\xi) < 1$. Whereas, $\gamma_u(\xi) = 1$ represents a scenario when no soft sensing information is used to adapt secondary user transmission power.

As shown in Fig. 3, secondary user's transmission power adapts to the soft sensing information obtained from spectrum sensor about PU activity, by transmitting at higher power levels when probability of primary user being inactive in shared channel is more i.e. $\gamma_u(\xi) > 1$. It may be noted that for peak received power equals to 0 dB, if primary receiver relaxed average received power constraint, ST can transmits at higher power levels to achieve high channel capacity.

The ergodic channel capacity of secondary user for Rayleigh fading channel and the corresponding optimum Lagrangian multiplier (λ_1) is shown in Figs. 4 and 5 respectively. In Fig. 4, the ergodic capacity is plotted for Rayleigh fading channel in bits/s/Hz verses P_{Avg} for different values of $\rho = \frac{P_{Peak}}{P_{Avg}}$. It can be observed that under a strict case with $\rho = 1$, there is significant capacity degradation when peak received power constraint is applied on the top of the average received power constraint. However, for a fixed value of P_{Avg}, ergodic capacity increases with an increase in ρ and converges towards the system with no peak received power constraint. Thus, it is anticipated that higher channel capacity may be achieved by relaxing peak received power constraint (higher P_{Peak}) at PU receiver, but, after a certain value of ρ, the ergodic capacity is limited by average received power constraint and does not increase by increasing P_{Peak}.

The Lagrangian multiplier variation as a function of P_{Avg} for different values of ρ is shown in Fig. 5. For a particular value of P_{Avg}, λ_1 increases with an increase in the value of ρ and converge towards the case with no peak received power constraint. Moreover, it can also be observed that for given value of ρ, λ_1 decreases as the average received power constraint become more stringent (Fig. 5). Figure 6 shows the achievable SU channel capacity as a function of the average received power constraints under strict peak received power constraints at PU. For comparison sake, we have also considered the case with no peak power constraint at PU. It is evident from the graph that if no peak received power

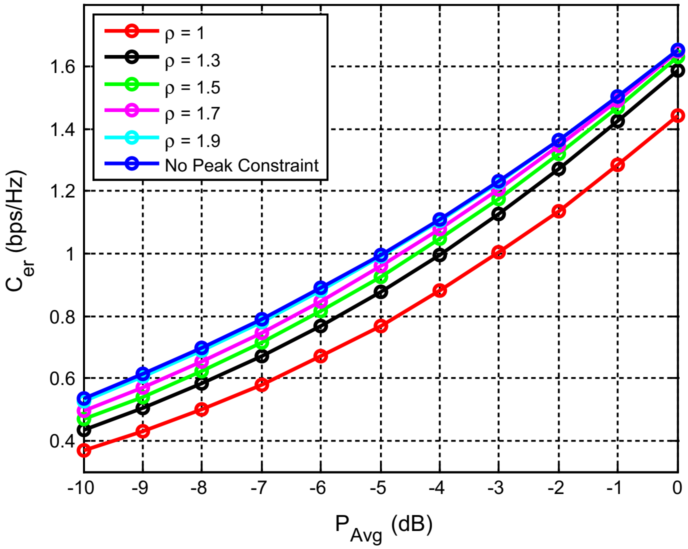


Fig. 4 Ergodic capacity verses average received power under adaptive transmission power scheme

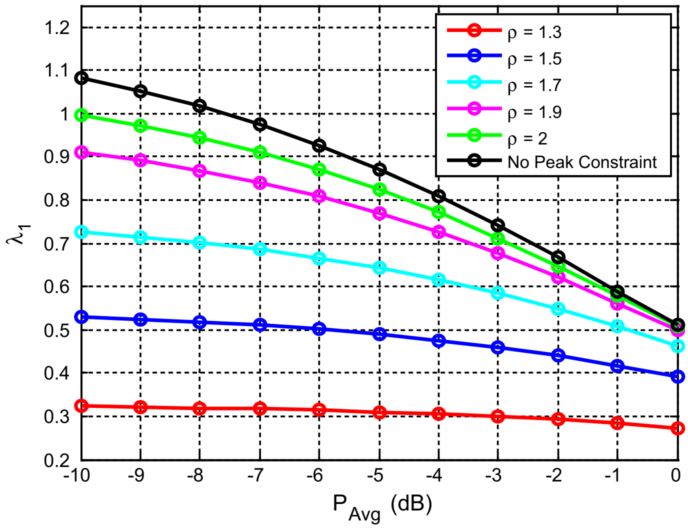


Fig. 5 Optimum Lagrangian parameter (λ_1) for Rayleigh fading channel under adaptive transmission power scheme

constraint is imposed over SU transmission power, the channel capacity can be enhanced significantly by relaxing average received inteference power constraint. However, to avoid interfernce to the PU in worst case, its important to limit the peak received interference power to it. From Fig. 6 it is evidant that the proposed communication system limits the the channel capacity when average received interference power become equal to the peak received interfernce power.

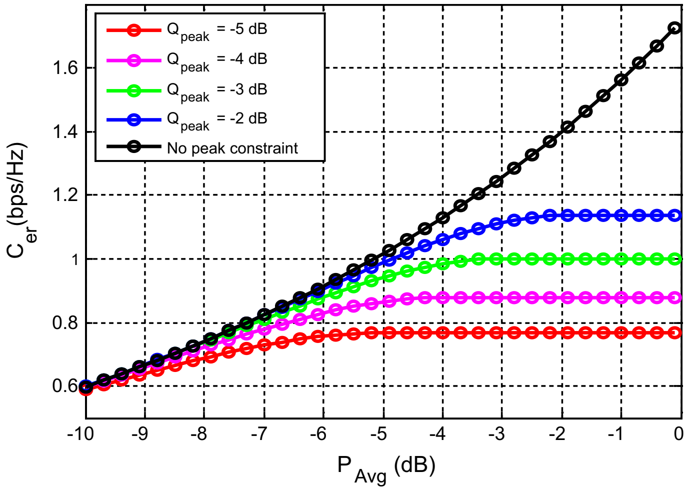


Fig. 6 Ergodic capacity under joint peak and average received power constraint for different values of P_{Peak}

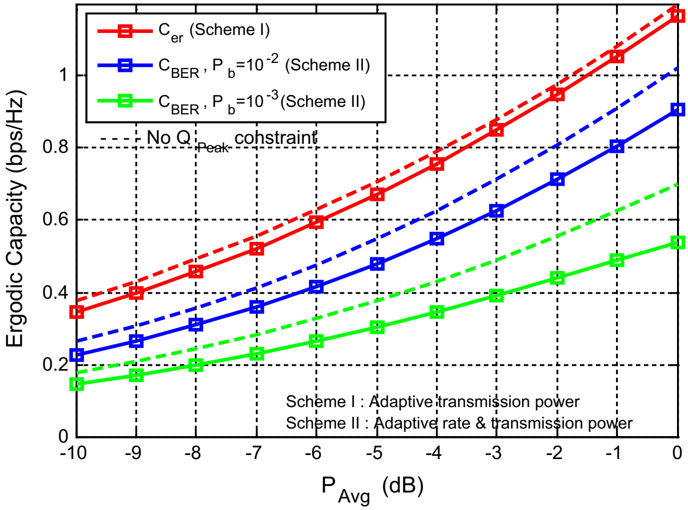


Fig. 7 Ergodic capacity under Adaptive Rate and Transmission Power M-QAM Scheme for $\rho = 1.7$

5.2 Ergodic Capacity for Adaptive Rate and Transmission Power M-QAM Scheme

The ergodic channel capacity of secondary user under adaptive rate and transmission power using M-QAM for Rayleigh fading is illustrated in Fig. 7, as a function of P_{Avg}. The scheme is evaluated for different BER requirements, for example we have assumed BER $= 10^{-2}$ and 10^{-3} here. For comparison purpose, ergodic capacity achieved by SU under scheme I (i.e. Adaptive Transmission Power Scheme) is also plotted. It is observed that there is a significant capacity loss in scheme II (i.e. Adaptive Rate and Adaptive

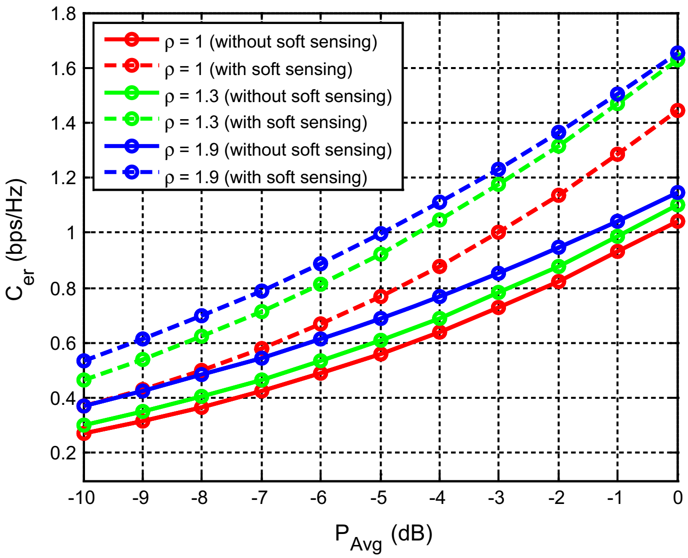


Fig. 8 Comparison between capacities with and without soft sensing information use for different values of ρ

Transmission Power M-QAM Scheme) due to parameter C. It may be noted that this capacity loss is independent to the soft sensing information and power constraints, and accordingly, C is the maximum coding gain for scheme II.

To illustrate the benefit of soft sensing information obtained from spectrum sensor on SU power control, the comparison between SU capacities with and without soft sensing information for different values of ρ is shown in Fig. 8. The graph reveals that soft sensing information used for SU power control result higher ergodic capacity for the same value of ρ.

6 Conclusions

In this paper, we have considered an opportunistic spectrum sharing scenario where secondary user adapts its transmission power and rate based on soft sensing information obtained from spectrum sensor in Rayleigh fading environment. The ergodic channel capacity of secondary communication system is assessed under joint peak and average received power constraint at primary receiver for two different adaptation schemes such as Adaptive Transmission Power Scheme and Adaptive Rate and Transmission Power Scheme. In this context, closed form expressions are obtained for ergodic capacity of SU for both transmission power control schemes. It is illustrated that the knowledge of the soft sensing information about PU activity in shared channel helps SU to transmit strongly when PU is absent and therefore, increases the channel capacity under joint peak and average received power constraints at the primary receiver. Moreover, it has also been observed that adaptive transmission power scheme offers more capacity than adaptive rate and transmission power scheme for given BER.

Appendix

To compute inner integration in (25), we need integration limit on soft sensing metric ξ. From (19), we have

$$\alpha + \bar{\alpha}\frac{f_{off}(\xi)}{f_{on}(\xi)} = \gamma_u(\xi)$$

Using (3) and (4), it becomes

$$\frac{(\xi - \mu_{off})^2}{2\delta_{off}^2} - \frac{(\xi - \mu_{on})^2}{2\delta_{on}^2} + \log\left(\frac{\delta_{off}}{\delta_{on}}\left(\frac{\gamma_u(\xi) - \alpha}{\bar{\alpha}}\right)\right) = 0 \tag{41}$$

$$\xi^2\left(\frac{1}{2\delta_{off}^2} - \frac{1}{2\delta_{on}^2}\right) + \xi\left(\frac{\mu_{on}}{\delta_{on}^2} - \frac{\mu_{off}}{\delta_{off}^2}\right) + \frac{\mu_{off}^2}{2\delta_{off}^2} - \frac{\mu_{on}^2}{2\delta_{on}^2} + \left(\frac{\delta_{off}}{\delta_{on}}\left(\frac{\gamma_u(\xi) - \alpha}{\bar{\alpha}}\right)\right) = 0 \tag{42}$$

$P_1(\gamma_u(\xi))$ and $P_2(\gamma_u(\xi))$ are the roots of quadratic equation in (42), and given by

$$P_1(\gamma_u(\xi)), P_2(\gamma_u(\xi)) = \frac{1}{2a}\left(-b \pm \sqrt{b^2 - 4ac}\right) \tag{43}$$

where

$$a = \left(\frac{1}{2\delta_{off}^2} - \frac{1}{2\delta_{on}^2}\right) \tag{44}$$

$$b = \left(\frac{\mu_{on}}{\delta_{on}^2} - \frac{\mu_{off}}{\delta_{off}^2}\right) \tag{45}$$

$$c = \frac{\mu_{off}^2}{2\delta_{off}^2} - \frac{\mu_{on}^2}{2\delta_{on}^2} + \left(\frac{\delta_{off}}{\delta_{on}}\left(\frac{\gamma_u(\xi) - \alpha}{\bar{\alpha}}\right)\right) \tag{46}$$

Using $P_1(\gamma_u(\xi))$ and $P_2(\gamma_u(\xi))$ as inner integration limit in (25), we get (27), thus completing the proof.

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Indu Bala has received her B.Tech. and M.Tech. degree in Electronics and Communication Engineering from Punjab Technical University, Jalandhar in 2003 and 2008 respectively. She is currently working towards her Ph.D. degree in the Electronics and Communication Department at the Punjabi University, Patiala, India. Her research interests include cognitive radio networks, dynamic spectrum access, interference mitigation and power allocation for cognitive radio networks.

Manjit Singh Bhamrah graduated in Electronics and Communication Engineering from Panjab University, Chandigarh, India in 1994. He received his M.Tech. (ECE) and Ph.D. in Optical Communication Systems from Punjab Technical University, Jalandhar in 2003 and 2011 respectively. Presently, he is a professor in ECE department of Punjabi University, Patiala. He has more than 17 years of teaching experience at UG and PG level at different colleges/universities of repute. He is author/co-author of more than 50 scientific papers of the refereed Journal and International Conferences. He has supervised various Ph.D. and M.Tech. theses. He is a very active speaker and had delivered more than 30 expert talks in AICTE sponsored programmes and other FDP's in India. He is also a faculty in charge academic affairs of the institute and had developed curriculum for UG and PG programmes. He is a reviewer in many international journals and a section editor of journal "International Journal of Information and Telecommunication Technology. He is a fellow member of Optical society of India (OSI) and member of Indian Society of Technical Education (ISTE). His area of interest is optical fiber communication, next generation networks and wireless communication.

Ghanshyam Singh received Ph.D. degree in Electronics Engineering from the Indian Institute of Technology, Banaras Hindu University, Varanasi, India, in 2000. He was associated with Central Electronics Engineering Research Institute, Pilani, and Institute for Plasma Research, Gandhinagar, India, as a Research Scientist. He was an Assistant Professor at ECE Department of Nirma University of Science and Technology, Ahmadabad, India and a Visiting Researcher at the Seoul National University, Seoul, South Korea. At present, he is Professor with the Department of Electronics and Communication Engineering, Jaypee University of Information Technology, Wakanaghat, Solan, India. He is an author/co-author of more than 185 scientific papers of the refereed Journal and International Conferences. His research and teaching interests include RF/Microwave Engineering, Millimeter/THz Wave Antennas, Next Generation Communication Systems and Nanophotonics. He has supervised various Ph.D. and M.Tech. theses. He has worked as a reviewer for several reputed Journals and Conferences. He is author of two books ''Terahertz Planar Antennas for Next Generation Communication'' and ''MOSFET Technologies for Double-Pole Four-Throw Radio-Frequency Switch'' published by Springer.