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Analysis of capacity limits over fading environment with imperfect channel state information for cognitive radio network

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Abstract In this paper, we have explored an optimal power allocation scheme for the spectrum sharing with imperfect channel state information between the cognitive/secondary user (CU) and licensed/primary user (PU) in the Rayleigh fading environment. We have analyzed the ergodic capacity of CU link under the combination of peak transmit power and peak/average interference power constraints with or without the primary user interference. In addition to this, the outage capacity with multiple primary users' interference is also analyzed with the error variance under the joint peak transmit power and peak interference power constraint as well as individual peak interference power constraint. Moreover, the power disbursement is also investigated to achieve the lower limit of ergodic and outage capacity. The minimum mean square channel estimation technique is used for the channel estimation between CU and PU. Further, the convex optimization method is used for the optimal power allocation.

Keywords Cognitive radio · Ergodic capacity · Outage probability · Minimum mean square error · Power consumption

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1 Introduction

Next generation wireless networks are emphasized on the seamless connectivity of all types of devices/networks and communication protocols, which have been set by the regulatory authorities to fulfill the consumer requirements. To yield the higher data rate and lower latencies, the next generation communication network has to be implemented with revolutionary ideas of using the radio spectrum, which is becoming very scarce as almost all the frequencies are already occupied by the licensed users. However, the usage of frequency spectrum varies temporally and geographically as per the report of FCC [1] and to accommodate more and more number of users within the limited spectrum is a challenging task.

The cognitive radio with spectrum sharing approach has been proposed as a solution to this apparent spectrum scarcity and can enhance the spectrum utilization if the primary (license spectrum) users allow secondary (unlicensed) users to access the licensed spectrum provided that the primary users are protected from the interference of cognitive users [2]. The cognitive radio communication technology is used to reduce the crowd of unlicensed users by using the large portion of unused licensed spectrum with context to the time and location [2, 3]. Moreover, various standardization bodies have developed different standards for cognitive radio network and the dynamic spectrum access network in order to incorporate with the existing wireless technologies such as IEEE 802.22 std. wireless regional area network, IEEE 802.11af standard for TV white spaces operation, and IEEE 1900 standard for spectrum access network [4]. On this fashion, the enhanced spectral efficiency is harvested through the novel networking paradigm that involve for utilization of unused radio spectrum through the cognitive radio, which is an emerging technology for the next generation wireless communication systems. Moreover, the design of its wireless system

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requires the collaborative efforts of various research communities such as communication theory, network engineering, signal processing, game theory, reconfigurable antenna and radio frequency design [5–7].

In this paper, the ergodic and outage capacity of CU link with or without the primary users' interference have been investigated in the Rayleigh fading environment under the joint transmit power and interference power constraints, when the imperfect channel state information (CSI) between the cognitive user transmitter (CU-Tx) and primary/licensed user receiver (PU-Rx) is accessed by CU-Tx. The main contributions of this article are summarized as follows.

- A simple optimal power allocation scheme for efficient spectrum sharing with imperfect CSI between the CU and PU in the Rayleigh fading environment is presented.
- The average power consumption of the cognitive radio transmitter under the joint peak transmit power and peak interference power constraints is investigated to achieve the lower limits of ergodic and outage capacities.
- The outage probability and consumption of power under the individual peak interference power constraint is explored.

The remainder of this paper is structured as follows. We have reviewed the related work in Section 2. In Section 3, we have described the proposed system model. In Section 4, the power constraint under which the transmission power is allocated to the cognitive user has been discussed. In Section 5, the ergodic and outage capacity under the Rayleigh fading channel of the proposed communication system is evaluated and the numerical simulation results are discussed and finally, Section 6 concludes the work and recommends the future scope.

2 Related work

The spectrum access strategy is one of the important research issues in the cognitive radio communication network in order to provide efficient spectrum allocation to the cognitive users. Various spectrum sharing approaches have been discussed in literatures [8–10]. In [8], the CSI between CU transmitter and the PU receiver is employed to compute the maximum allowable CU's transmit power to limit the interference. In addition to this, a closed-form mathematical expression for the CU's capacity under the peak received interference power constraint and CU's transmit power constraint has been derived. In [9], the authors have explored the cooperative communications for spectrum sharing in a cognitive wireless relay network, and cognitive space-time-frequency coding technique which can adjust opportunistically its coding structure by adapting itself to the dynamic spectrum access environment, is exploited to maximize the spectrum opportunities. Wang and Zhang [10] have investigated an opportunistic spectrum access technique in the cognitive radio networks when decode-and-forward relay is employed. Furthermore, two cognitive spectrum access approaches are proposed based on white space modeling, referred as successive sensing based spectrum access and simultaneous sensing based spectrum access.

In addition to the efficient spectrum allocation, the energy efficiency of network is also an emerging concern, therefore several novel power allocation strategies are proposed by various researchers under different spectrum sharing approaches [11–13]. In [11], the authors have studied the optimal power allocation strategies to achieve the ergodic as well as outage capacity of the CU fading channel under different types of power constraints. In addition to the interference power constraint on PU, the transmit power constraint of CU is also considered because the transmit power and the interference power is limited either by a peak or an average power constraint. Kim et al. [12] have examined the dynamic spectrum sharing problem among the primary and secondary users in a cognitive radio network by considering the scenario where the primary users' exhibit on-off behavior, and the CUs are able to dynamically measure/estimate sum interference from the primary users at their receiving ends, and solve the problem of fair spectrum sharing among the CUs subject to their quality-of-service (QoS) constraints as well as interference power constraints for the primary users. In [13], a resource allocation framework considering both the interference power constraints for the primary users and QoS constraints for the cognitive users is exploited for spectrum underlay approach in the cognitive wireless networks particularly; the interference from the CUs to primary users is controlled below a tolerable limit. Furthermore, the admission control algorithms are used during the high network load conditions which perform jointly with the power control so that the QoS requirements of all the admitted CUs are satisfied while keeping the interference to primary users below the tolerable limit. Li [14] has proposed an efficient power allocation algorithm for centralized as well as distributed cognitive radio network, when a pair of the primary users and multiple pairs of CUs are in the network. In [15], an effective capacity of the CU link is evaluated under the signal-to-interference noise ratio (SINR) and QoS constraints. In [16], the geometric programming approach is used for the optimal power allocation to CUs under different channel conditions in order to compute the secondary link capacity. Parsaeefard and Sharafat [17] have proposed an algorithm for the distributed uplink power allocation in underlay cognitive radio network with imperfect CSI and illustrated that the robustness in network is introduced at the cost of social utility.

The channel capacity is the best performance metric to analyze any cognitive radio network model, and several capacity notions are expressed for different fading channels such as the ergodic capacity for fast-fading channel and outage capacity for the slow-fading channel [18]. Various researchers/scientists have analyzed the capacity limits of the CU's link over different fading environments with perfect/imperfect CSI [19, 20]. Rezki and Alouini [19] have presented a cognitive radio communication system in which the CUs are aware of instantaneous CSI of the secondary link but know only the statistics of an estimated version of the secondary transmitter-primary receiver link. The mathematical expression for optimum power profile and ergodic capacity of the secondary link are derived for general fading channels with a continuous probability density function (pdf) under the average and peak transmit power constraints. In [20], the authors have analyzed the capacity gains of an opportunistic spectrum sharing channels in the fading environments with perfect and imperfect CSI and derive the ergodic and outage capacities along with their optimum power allocation policies for the Rayleigh flat-fading channels, and provide the closed-form expressions for these capacity metrics considering the average received-power constraint. Recently, Farraj and Ekin [21] have illustrated that the capacity and bit-error-rates are independent from the transmitted power of CU, however, these metric are affected by the environmental parameters such as shaping parameters. In [22], the authors have reported the ergodic sum capacity limits of CUs under transmit power and interference power constraints, when the multiple primary users' network and CUs network is present. Son et al. [23] have presented the power allocation policies in OFDM-based cognitive radio networks under the availability of inter-system (between the CU-Tx and PU-Rx) CSI with different capability of primary users particularly; the peak interference power as well as average interference power tolerable to the primary user. Moreover, for such primary users' model, two optimization problems which maximize the capacity of CUs while maintaining the QoS of primary user under the assumption that both intra- (between the CU-Tx and CU-Rx) and inter-system CSI are fully available has also been discussed. However, due to lose cooperation between CU and primary user, it may be difficult or even infeasible for CU to obtain the full inter-system CSI, thus under the partial CSI, the authors also formulated another two optimization problem by introducing interference power outage constraints. The extensive numerical results illustrate that the spectral efficiency achieved by CUs with partial inter-system CSI within a reasonable range of outage probability. The spectral efficiency achieved by CUs with partial-CSI is less than half of that is achieved with full-CSI with a reasonable change of the outage probabilities [23]. If the CUs share the bandwidth of channel with PU using the dynamic spectrum access technique then the outage capacity with N number of multiple carriers has a variance which is N times smaller than that of the single carrier [24]. The CUs support PU to improve the QoS by using inactive unlicensed users as cooperative relay nodes for the primary user [25, 26]. The CU link with high channel gain achieves better channel capacity when the multiple CUs share the spectrum with single PU [27]. However, the joint congestion control and power control problem via effective network utility maximization with the link outage constraints have been explored in [28]. In [29], it has been reported that the average transmit power consumption of CU is significantly more under the interference temperature constraint. Moreover, the variations of outage probability under the peak transmit power and peak/average interference power with noise error variance is presented in [30]. Recently, Pandit and Singh [31] have achieved significantly more capacity by adaptive power transmission technique in comparison to that of the adaptive rate and power transmission policy at the cost of bit-error-rate (BER). In [32], the authors derived the closed-form expressions for the ergodic capacities of the CUs with imperfect CSI under the average interference power constraint and peak interference power constraint. It is illustrated that the ergodic capacity of the CU is robust to the channel estimation errors and feedback delay. Further, it is also shown that with decreasing the distance between CU-Tx and CU-Rx or increasing the distance between CU-Tx and PU-Rx can mitigate the impact of imperfect CSI and significantly increase the ergodic capacity of the CUs.

Li and Goldsmith [33] have studied three types of capacity regions such as the ergodic capacity region, the zero-outage capacity region, and the outage capacity region with non-zero outage for the fading broadcast channels, and obtain their corresponding optimal resource allocation strategies. In [34], the authors have derived the mathematical expression of outage capacity for fading broadcast channels considering both the transmitter and receivers have perfect CSI and locate a strategy which bounds the outage probability of different spectrum-sharing techniques for specified required rate of each user. The corresponding optimal power allocation scheme is a multiuser generalization of the threshold-decision rule for a single-user fading channel. The numerical results for different outage capacity regions are obtained for the Nakagami-*m* fading model. Gastpar [35] has investigated the behavior of capacity when the constraints are placed on the channel output signal. This investigation was motivated by questions arising in spectrum sharing and dynamic spectrum allocation—multiple independent networks share the same frequency band, but are spatially mostly disjoint. Sboui et al. [36] have considered a spectrum sharing communication scenario in which the primary users and CUs are communicating simultaneously, with their respective destinations using the same carrier frequency. The mathematical expression for both the optimal power profile and ergodic capacity is derived for fading channels under the average transmit power and instantaneous interference outage constraints. After deriving the expression for capacity considering a noisy version of the cross-link and secondary-link CSI, the authors have provided an ergodic capacity generalization through a unified expression that encompasses several previously studied spectrum sharing settings. Musavian and Aissa [37], have presented the fundamental capacity limits of opportunistic spectrum-sharing channels in the fading environment and derived the fading channel capacity of a CU subject to both the average- and peak-received power constraints at the PU receiver. In addition to this, the mathematical expressions are derived for the capacity and optimum power allocation scheme for three different capacity notions, namely, ergodic, outage, and minimum-rate, considering the flat Rayleigh fading.

3 System model

In the proposed system model, we have considered multiple PUs and single CU which transmit data/information at same time. The CU shares spectrum with one of the PU without affecting its QoS. For the interference-free spectrum sharing, the optimal power is allocated to the CU under the joint transmit power and received interference power constraints. We have also considered the discrete time flat fading channel where the received signal of CU depends on the transmitted signal, which is mathematically expressed as [18]:

$$y_{ss}(n) = x_{ss}(n)h_{ss}(n) + \sum\nolimits_{i=1}^{n} x_p(n)h_{psi}(n) + w_{ss}(n) \quad (1)$$

where n, $h_{ss}(n)$, $h_{sp}(n)$, and $h_{ps_i}(n)$ are the time index, channel gain of the CU link, channel gain between CU-Tx and PU-Rx link, and channel gain between ith PU-Tx and CU-Rx link, respectively. Further, the $h_{ss}(n)$, $h_{sp}(n)$, and $h_{ps_i}(n)$ are the independent and identically distributed (iid) channel gain with exponential distribution. $w_{ss}(n)$ is the zero-mean complex symmetric additive white Gaussian noise (AWGN) Fig. 1.

In the proposed system model, the capacity of CU has been maximized while maintaining the QoS of PU under

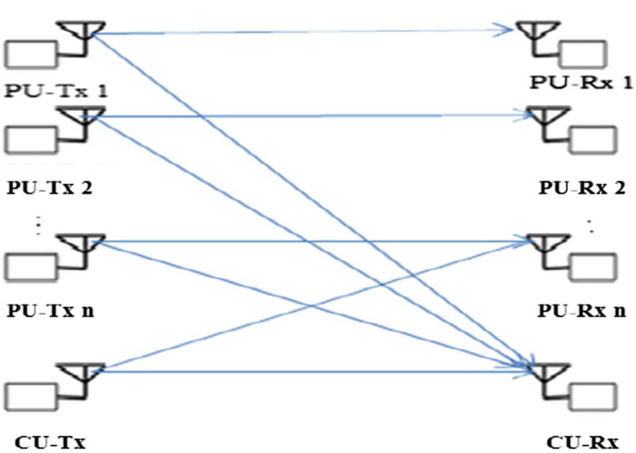


Fig. 1 The spectrum sharing system model of cognitive radio network

the assumption that both the intra-and inter-system channel state information are partially/imperfectly available due to lose cooperation between the CU and PU. The imperfect CSI is provided to CU-Tx by ith PU, which is represented as $\breve{h}_{sp_i}(n)$. Thus under the imperfect CSI, the ergodic capacity and outage capacity have been computed. However, the CU estimates the channel gain by minimum mean square error (MMSE) channel estimation technique. The imperfect CSI in the proposed cognitive radio communication system has been described as follows. The CU-Tx has knowledge only about the average channel gain over all the subchannels instead of individual channel gain for each subchannel. In order to keep the interference at the PU-Rx below a desired level as reported in literature [38] assumed that the CU-Tx is fully aware of channel from the CU-Tx to PU-Rx. However, as compared to the intra-system CSI between the CU-Tx and the CU-Rx is relatively easy to obtain. It would be difficult for the CU-Tx to obtain full inter-system CSI because the PU and CU systems are usually loosely coupled (no explicit communication between them). Even if they are tightly coupled, to yield inter-system CSI is difficult for the CU due to the large amount of feedback overhead. Therefore, considering only the imperfect CSI between the CU and PU seems to be reasonable approach. Zhang et al. [39] have presented a vigorous cognitive beam-forming difficulty with imperfect CSI in multi-input-single-output (MISO) and multi-input-multi-output (MIMO) environments. Further, there are several studies on the capacity analysis of cognitive radio network with imperfect channel knowledge in flat-fading environment and consider that the CSI obtained by CU, experience the channel estimation error [40]. The channel estimation error is represented as:

$$\tilde{h}_{spi}(n) = h_{spi}(n) - \hat{h}_{spi}(n) \quad (2)$$

where $\tilde{h}_{spi}(n)$ and $\hat{h}_{spi}(n)$ are the zero-mean circularly symmetric complex Gaussian distributed random variable with variance $(\sigma^2/2)$ and $(1-\sigma^2)/2$, respectively, and we have ignored the time index for simplicity. Due to the MMSE estimation characteristics, $\tilde{h}_{spi}$ and $\hat{h}_{spi}$ are the uncorrelated channel gain. However, the channel power gain is given by $|h_{sp}|^2$, and the channel power gain of the CU link between the CU-Tx and PU-Rx link and ith PU-Tx and CU-Rx link are represented by g_{ss}, g_{spi}, and g_{ps}, respectively.

4 Ergodic and outage capacity

The ergodic capacity is an effective metric for the fast fading channels or delay insensitive applications, where the block of information can experience different fading states of the channel during transmission, whereas the slower fading channels are delay sensitive applications like voice and video transmission, the outage capacity comprises a more suitable metric for the capacity of system due to fact that only a cross section of the channel characteristics is experienced during the transmission period of a block of information.

4.1 Power constraints

We have considered P_{pk} and Q_{pk} as the peak transmit power of CU and peak interference power of PU-Rx, respectively. The instantaneous transmitted power of CU-Tx depends on the channel power gain g_{ss} and the estimated value g_{sp} which is denoted by $\hat{g}_{sp}$. However, the instantaneous power at the CU-Tx is expressed as [11]:

$$P\left(\hat{g}_{sp1},\hat{g}_{sp2}..\hat{g}_{spn},g_{ss}\right) > 0, \forall\left(\hat{g}_{sp1}..\hat{g}_{spn},g_{ss}\right) \tag{3}$$

and the peak transmit power constraint is represented as [11]:

$$P\left(\hat{g}_{sp1},\hat{g}_{sp2}..\hat{g}_{spn},g_{ss}\right)\leq P_{pk}, \forall\left(\hat{g}_{sp1}..\hat{g}_{spn},g_{ss}\right) \tag{4}$$

as well as the peak interference power constraint is provided as [11]:

$$g_{spi}P\left(\hat{g}_{sp1},\hat{g}_{sp2}..\hat{g}_{spn},g_{ss}\right)\leq Q_{pki},\forall\left(\hat{g}_{sp1}..\hat{g}_{spn},g_{ss}\right),$$

$$i = 1..n \tag{5}$$

However, the instantaneous peak interference power constraint is valid only for the short time. Due to this reason, the interference outage concept is introduced by Musavian and Aissa [20]. Therefore, the outage interference power constraint is represented as [20]:

$$P_r\left\{g_{spi}\left(P\left(\hat{g}_{sp1},\hat{g}_{sp2}..\hat{g}_{spn},g_{ss}\right)\right)\geq Q_{pki}\right\}\leq P_0 \tag{6}$$

where $P_{\text{r}}\{.\}$ and P_0 are the probability of function and outage interference level, respectively. Therefore, the Eq. (6) can be simplified as:

$$P\left(\hat{g}_{sp1},\hat{g}_{sp2}..\hat{g}_{spn},g_{ss}\right)\leq\min\left(\frac{Q_{pki}}{\hat{g}_{spi}-\sigma^2 lnP_0}\right),\quad i = 1..n \tag{7}$$

In addition to this, the average interference power constraint is expressed as:

$$E\left[g_{spi}\,P\left(\hat{g}_{sp1},\hat{g}_{sp2}..\hat{g}_{spn},g_{ss}\right)\right]\leq Q_{\text{avgi}}, i = 1..n \tag{8}$$

due to the imperfect CSI, the g_{spi} is unknown. Therefore, the estimated value of g_{spi} is expressed as:

$$\hat{g}_{spi} = g_{spi} - \tilde{g}_{spi} \tag{9}$$

where $\hat{g}_{spi}$, g_{spi} and $\tilde{g}_{spi}$ are the estimated, ideal (true) and estimated error values of the g_{sp}, respectively. Therefore, the average interference power constraint is expressed as [20]:

$$E\left[\hat{g}_{spi}P\left(\hat{g}_{sp1},\hat{g}_{sp2}..\hat{g}_{spn},g_{ss}\right)\right]\leq Q_{\text{avgi}}-\sigma^2 E\left[P\left(\hat{g}_{sp1},\hat{g}_{sp2}..\hat{g}_{spn},g_{ss}\right)\right] \tag{10}$$

For the optimal transmit power computation, the combination of instantaneous CU-Tx power, peak transmit power of CU and outage constraint is represented by R_1. Further, the combination of instantaneous CU-Tx power, peak transmit power of CU and average interference power constraint is represented by R_2.

4.2 Ergodic capacity

The ergodic capacity is the maximum achievable rate averaged over all the fading states [11]. Therefore, the ergodic capacity of cognitive link is computed by solving the optimization problem as discussed in [11].

$$C_{ergodic} = \max_{P\left(\hat{g}_{sp1},\ \hat{g}_{sp2},\ \ldots\ \hat{g}_{spn},\ g_{ss}\right)\in R} E\left[\log_2\left(1+\frac{g_{ss}.P\left(\hat{g}_{\text{sp}},g_{ss}\right)}{N_o.B+\sum_{i=1}^{n} g_{ps}*P_i)}\right)\right] \tag{11}$$

where E{.} is the expected value and g_{ss}, g_{ps}, and $\hat{g}_{sp}$ follow the Rayleigh distribution whose probability density function (pdf) is specified as: $e^{-g_{ss}}$, $e^{-g_{ps}}$ and $e^{-\hat{g}_{sp}/\left(1-\sigma^2\right)}/(1-\sigma^2)$, respectively [19]. When the multiple primary users are considered then pdf of the channel power gain between the cognitive transmitter and primary receivers is evaluated as follows. Let $\hat{g}_{spi}$ (i = 1...n) be iid random variables. It is assumed that the channel gain of cognitive link is independent from the channel gain between the cognitive transmitter and primary receivers. Therefore, $\hat{g}_{sp}$ is expressed as:

$$\hat{g}_{sp} = \max\left(\hat{g}_{spi}\right)\quad i = 1..n$$

Then the cumulative distribution function of $\hat{g}_{sp}$ is presented as:

$$F_{\hat{g}_{sp}}\left(\hat{g}_{sp}\right) = \prod_{i=1}^{n} F_{\hat{g}_{spi}}\left(\hat{g}_{sp}\right) = \left(1-e^{-\frac{\hat{g}_{sp}}{1-\sigma^2}}\right)^n \tag{12}$$

On differentiating Eq. (12), the pdf of $\hat{g}_{sp}$ is written as:

$$f_{\hat{g}_{sp}}\left(\hat{g}_{sp}\right) = n\frac{e^{-\frac{\hat{g}_{sp}}{1-\sigma^2}}}{1-\sigma^2}\left(1-e^{-\frac{\hat{g}_{sp}}{1-\sigma^2}}\right)^{n-1} \tag{13}$$

Similarly, the pdf for multiple primary transmitter and cognitive receiver is given as:

$$f_{g_{ps}}\left(g_{ps}\right) = n\, e^{-g_{ps}}\left(1-e^{-g_{ps}}\right)^{n-1} \quad (14)$$

However, both the channels are considered as the Rayleigh fading channel, and the probability density function of $\widehat{g_{sp}}$ and g_{ss} are represented as: $e^{-\hat{g}_{sp}/\left(1-\sigma^2\right)}/\left(1-\sigma^2\right)$ and $e^{-g_{ss}}$, respectively as discussed in [19]. N_0 and B are the noise power spectral density at primary receiver and total available bandwidth, respectively. Therefore, the ergodic capacity of cognitive radio user link can be maximized by allocating the optimal power to SU-Tx.

4.2.1 Optimal power allocation under peak transmit power and peak interference power constraint

The joint peak transmit power and peak interference power constraints are combined as follows:

$$\mathrm{P}\left(\hat{g}_{sp1}, \hat{g}_{sp2}, \ldots \hat{g}_{spn}, g_{ss}\right) \le \mathrm{P}\left(\min\left(\mathrm{P}_{pk}, \frac{\mathrm{Q}_{pki}}{\widehat{g_{spi}} - \sigma^2.\ln\mathrm{P}_0}\right)\right)$$

Therefore, to maximize the ergodic capacity, the optimal power allocation to the CU is given as:

$$P\left(\hat{g}_{sp1}, \hat{g}_{sp2}, \ldots \hat{g}_{spn}, g_{ss}\right) = \begin{cases} P_{pk}, & \widehat{g_{sp_i}} \le \dfrac{Q_{pki}}{P_{pk}} + \sigma^2 \ln P_0 \\ \dfrac{Q_{pki}}{\widehat{g_{spi}} - \sigma^2 \ln P_0}, & \text{otherwise} \end{cases} \quad (15)$$

From the Eq. (15), it is observed that when the outage interference constraint is satisfied then the CU transmit with peak power, otherwise the transmit power has to be reduced according to the channel power gain, error-variance and outage constraint.

4.2.2 Optimal power allocation under peak transmit power and average interference power constraint

The optimal power under the peak transmit power and the average interference power constraints are computed by using the Lagrangian method as reported in [41]:

$$L\left(P\left(\hat{g}_{sp1}, \hat{g}_{sp2}, \ldots \hat{g}_{spn}, g_{ss}\right), \lambda\right) = E\left(\log_2\left(1 + P\left(\hat{g}_{sp1}, \hat{g}_{sp2}, \ldots \hat{g}_{spn}, g_{ss}\right)\frac{g_{ss}}{N_0 B}\right)\right.$$
$$\left. -\lambda\left(E\left(\hat{g}_{sp} P\left(\hat{g}_{sp1}, \hat{g}_{sp2}, \ldots \hat{g}_{spn}, g_{ss}\right)\right) - Q_{av} + \sigma^2 E\left(P\left(\hat{g}_{sp1}, \hat{g}_{sp2}, \ldots \hat{g}_{spn}, g_{ss}\right)\right)\right)\right) \quad (16)$$

For particular fading state, the Eq. (16) can be represented as:

$$\max_{P\left(\hat{g}_{sp}, g_{ss}\right)} \log_2\left(1 + \frac{P\left(\hat{g}_{sp1}, \hat{g}_{sp2}, \ldots \hat{g}_{spn}, g_{ss}\right) g_{ss}}{\sum_{i=1}^{n} g_{psi} * P_i + \mathrm{N}_0\, \mathrm{B}}\right) - \lambda\left(\hat{g}_{sp} P\left(\hat{g}_{sp1}, \hat{g}_{sp2}, \ldots \hat{g}_{spn}, g_{ss}\right) - Q_{av}\right.$$
$$\left. + P\left(\hat{g}_{sp1}, \hat{g}_{sp2}, \ldots \hat{g}_{spn}, g_{ss}\right)\right) - \mu\left(P\left(\hat{g}_{sp1}, \hat{g}_{sp2}, \ldots \hat{g}_{spn}, g_{ss}\right) - P_{pk}\right) + v\, P\left(\hat{g}_{sp1}, \hat{g}_{sp2}, \ldots \hat{g}_{spn}, g_{ss}\right) \quad (17)$$
$$\text{s.t} \; P\left(\hat{g}_{sp1}, \hat{g}_{sp2}, \ldots \hat{g}_{spn}, g_{ss}\right) \ge 0, \; P\left(\hat{g}_{sp1}, \hat{g}_{sp2}, \ldots \hat{g}_{spn}, g_{ss}\right) \le P_{pk}$$

The dual function of Eq. (17) is represented as:

$$L\left(P\left(\hat{g}_{sp1}, \hat{g}_{sp2}, \ldots \hat{g}_{spn}, g_{ss}\right), \lambda, \mu, v\right) = \log\left(1 + \frac{P\left(\hat{g}_{sp1}, \hat{g}_{sp2}, \ldots \hat{g}_{spn}, g_{ss}\right)}{N_0 B}\right) \quad (18)$$
$$-\lambda\left(\hat{g}_{sp} P\left(\hat{g}_{sp1}, \hat{g}_{sp2}, \ldots \hat{g}_{spn}, g_{ss}\right) - Q_{av} + \sigma^2 P\left(\hat{g}_{sp1}, \hat{g}_{sp2}, \ldots \hat{g}_{spn}, g_{ss}\right)\right)$$
$$-\mu\left(P\left(\hat{g}_{sp1}, \hat{g}_{sp2}, \ldots \hat{g}_{spn}, g_{ss}\right) - P_{pk}\right) + v\, P\left(\hat{g}_{sp1}, \hat{g}_{sp2}, \ldots \hat{g}_{spn}, g_{ss}\right)$$

By using the Karush-Kuhn-Tucker (KKT) conditions, the optimal power is computed as:

$$\frac{\partial L\left(P\left(\hat{g}_{sp1}, \hat{g}_{sp2}, \ldots \hat{g}_{spn}, g_{ss}\right), \lambda, \mu, v\right)}{\partial P\left(\hat{g}_{sp1}, \hat{g}_{sp2}, \ldots \hat{g}_{spn}, g_{ss}\right)}$$
$$= \frac{g_{ss}}{\sum_{i=1}^{n} g_{psi} * P_i + N_0\, B + P\left(\hat{g}_{sp1}, \hat{g}_{sp2}, \ldots \hat{g}_{spn}, g_{ss}\right) g_{ss}} - \lambda\left(\hat{g}_{spi} + \sigma^2\right) - \mu + v = 0 \quad (19)$$

$$\mu\left(P\left(\hat{g}_{sp1},\hat{g}_{sp2},\ldots\hat{g}_{spn},g_{ss}\right)-P_{pk}\right)=0 \tag{20}$$

$$v\,P\left(\hat{g}_{sp1},\hat{g}_{sp2},\ldots\hat{g}_{spn},g_{ss}\right)=0 \tag{21}$$

From Eq. (19), we get:

$$P\left(\hat{g}_{sp1},\hat{g}_{sp2},\ldots\hat{g}_{spn},g_{ss}\right)=\frac{K}{\lambda\left(\hat{g}_{spi}+\sigma^2\right)+\mu-v}-\frac{\sum_{i=1}^{n}g_{psi}*P_i+N_0\,B}{g_{ss}} \tag{22}$$

If we consider, $P\left(\hat{g}_{sp1},\hat{g}_{sp2},\ldots\hat{g}_{spn},g_{ss}\right)<P_{pk}$, it is possible only if $\hat{g}_{sp}\geq\frac{K}{\lambda\left(P_{pk}+\frac{\sum_{i=1}^{n}g_{psi}*P_i+N_0\ B}{g_{ss}}\right)}-\sigma^2$, so it contradicts the assumption. Therefore,

$$P\left(\hat{g}_{sp1},\hat{g}_{sp2},\ldots\hat{g}_{spn},g_{ss}\right)=P_{pk}$$

if
$\hat{g}_{sp}\leq\frac{K}{\lambda\left(P_{pk}+\frac{\sum_{i=1}^{n}g_{psi}*P_i+N_0\ B}{g_{ss}}\right)}-\sigma^2.$

Suppose, if $P\left(\hat{g}_{sp1},\hat{g}_{sp2},\ldots\hat{g}_{spn},g_{ss}\right)>0$ when $\hat{g}_{sp}\geq\frac{K}{\lambda\left(P_{pk}+\frac{\sum_{i=1}^{n}g_{psi}*P_i+N_0\ B}{g_{ss}}\right)}-\sigma^2$ from Eq. (21) $v=0$ then Eq. (22) become:

$$P\left(\hat{g}_{sp1},\hat{g}_{sp2},\ldots\hat{g}_{spn},g_{ss}\right)=\frac{K}{\lambda\left(\hat{g}_{spi}+\sigma^2\right)+\mu}+\mu-\frac{\sum_{i=1}^{n}g_{psi}*P_i+N_0\ B}{g_{ss}}$$

then $P\left(\hat{g}_{sp1},\hat{g}_{sp2},\ldots\hat{g}_{spn},g_{ss}\right)>0.$

which results: $\frac{K}{\lambda\left(\hat{g}_{spi}+\sigma^2\right)+\mu}+\mu-\frac{\sum_{i=1}^{n}g_{psi}*P_i+N_0\ B}{g_{ss}}>0$

since $\mu\geq0$,

$$\frac{K}{\lambda\left(\hat{g}_{spi}+\sigma^2\right)}-\frac{\sum_{i=1}^{n}g_{psi}*P_i+N_0\ B}{g_{ss}}>\frac{K}{\lambda\left(\hat{g}_{spi}+\sigma^2\right)+\mu}-\frac{\sum_{i=1}^{n}g_{psi}*P_i+N_0\ B}{g_{ss}}>0,$$

Therefore, $P\left(\hat{g}_{sp1},\hat{g}_{sp2},\ldots\hat{g}_{spn},g_{ss}\right)=0$ if
$\hat{g}_{spi}\geq\frac{Kg_{ss}}{\lambda\left(\sum_{i=1}^{n}g_{psi}*P_i+N_0\ B\right)}-\sigma^2.$

and $P\left(\hat{g}_{sp1},\hat{g}_{sp2},\ldots\hat{g}_{spn},g_{ss}\right)=\frac{K}{\lambda\left(\hat{g}_{spi}+\sigma^2\right)}-\frac{N_0}{g_{ss}}$
if $\frac{K}{\lambda\left(P_{pk}+\frac{\sum_{i=1}^{n}g_{psi}*P_i+N_0\ B}{g_{ss}}\right)}-\sigma^2\leq\hat{g}_{spi}\leq\frac{Kg_{ss}}{\lambda\left(\sum_{i=1}^{n}g_{psi}*P_i+N_0\ B\right)}-\sigma^2.$

Therefore, the optimal power allocations under the peak transmit power and average interference power constraints are expressed as:

$$P\left(\hat{g}_{sp1},\hat{g}_{sp2},\ldots\hat{g}_{spn},g_{ss}\right)=\begin{cases}P_{pk} & \text{if } \frac{K}{\lambda\left(P_{pk}+\frac{N_0B}{g_{ss}}\right)}-\sigma^2\geq\hat{g}_{spi}\\ \frac{K}{\lambda\left(\hat{g}_{sp}+\sigma^2\right)}-\frac{N_0}{g_{ss}} & \text{if } \frac{K}{\lambda\left(P_{pk}+\frac{N_0B}{g_{ss}}\right)}-\sigma^2\leq\hat{g}_{sp}\leq\frac{Kg_{ss}}{\lambda N_0}-\sigma^2\\ 0, & \text{otherwise}\end{cases} \tag{23}$$

4.2.3 Power consumption of cognitive transmitter without primary users' interference

The average power consumption of CU-Tx under the peak transmit power and peak interference power constraint are expressed as:

$$E\left[P\left(\hat{g}_{spi}g_{ss}\right)\right]=P_{pk}-\frac{P_{pk}}{1-\sigma^2}\exp\left(\frac{Q_{pk_i}}{P_{pk}}+\sigma^2log(P_0)-\frac{Q_{pki}}{1-\sigma^2}exp\left(-\sigma^2log(P_0)\right)Ei\left(-\frac{Q_{pki}}{P_{pk}(1-\sigma^2)}\right)\right) \tag{24}$$

4.3 Outage capacity

The outage capacity is the maximum transmission rate that can be maintained over the fading blocks with a given outage probability [11]. The objective function of outage capacity is expressed as:

$$\Pr\left\{\log_2\left(1+\frac{g_{ss}\ P\left(\hat{g}_{sp1},\hat{g}_{sp2},\ldots\hat{g}_{spn},g_{ss}\right)}{\sum_{i=1}^{n}g_{psi}*P_i+N_0\ B}\right)\right\}\leq P\left(\hat{g}_{sp1},\hat{g}_{sp2},\ldots\hat{g}_{spn},g_{ss}\right)\in R\min r_0 \tag{25}$$

where, $R\in\{R_1,R_2\}$. N_0, B, g_{psi}, and P_i are the noise power spectral density at PU-Rx, total available bandwidth, channel power gain between ith PU-Tx and CU-Rx and power transmitted by PU-Tx, respectively.

4.3.1 Optimal power allocation under peak transmit power and peak interference power constraint

For the optimal power allocation $R\in R_1$ and two dimensional truncated channel inversions (2D–TCI) strategy is used over $\hat{g}_{sp}$ and g_{ss}. Therefore, the optimal transmit power of cognitive user is expressed as:

$$P\left(\hat{g}_{sp1},\hat{g}_{sp2},\hat{g}_{sp3}\cdots\hat{g}_{spn},g_{ss}\right)=\begin{cases}\dfrac{\left(N_oB+\sum_{i=1}^{n}g_{ps}{*}P_i\right)\left(2^{r_o}-1\right)}{g_{ss}}, & g_{ss}\geq\dfrac{\left(2^{r_0}-1\right)\left(N_oB+\sum_{i=1}^{n}g_{ps}{*}P_i\right)}{P_{pk}}\ and\\ & \hat{g}_{spi}\leq\dfrac{g_{ss}Q_{pk}}{\left(N_oB+\sum_{i=1}^{n}g_{ps}{*}P_i\right)\left(2^{r_0}-1\right)}+\sigma^2ln(P_0)\\ 0, & \text{otherwise}\end{cases}\tag{26}$$

Let, $\dfrac{g_{ss}Q_{pk}}{\left(N_oB+\sum_{i=1}^{n}g_{ps}{*}P_i\right)\left(2^{r_0}-1\right)}+\sigma^2ln(P_0)$

and

$$\frac{\left(2^{r_0}-1\right)\left(N_oB+\sum_{i=1}^{n}g_{ps}{*}P_i\right)}{P_{pk}}$$

is denoted by the auxiliary variables u and z, respectively. By substituting Eq. (26) in Eq. (25), we yield the outage probability as:

$$P_{out}=1-\iiint f_{\hat{g}_{sp}}\left(\hat{g}_{sp}\right)f_{g_{ss}}(g_{ss})f_{g_{ps}}\left(g_{ps}\right)\,d\hat{g}_{sp}\,dg_{ss}\,dg_{ps}\tag{27}$$

where, $f_{\hat{g}_{sp}}(\hat{g}_{sp})$, $f_{g_{ps}}\left(g_{ps}\right)$ and $f_{g_{ss}}(g_{ss})$ are the probability density function of $\hat{g}_{sp}$, g_{ps} and g_{ss}, respectively. The outage capacity for the Rayleigh fading channel is computed as:

$$C_{outage}=log_2\left(1+F^{-1}(1-P_{out})\,\gamma\right)\tag{28}$$

where $F(x)=\Pr(g_{ss}>x)$is the complementary cumulative distribution function of g_{ss} and γ is signal-to- noise ratio (SNR) [18].

4.3.2 Optimal power allocation under peak interference power constraint

$$P\left(\hat{g}_{sp1},\hat{g}_{sp2}..\hat{g}_{spn},g_{ss}\right)=min\left(\frac{Q_{pki}}{\hat{g}_{spi}-\sigma^2lnP_0}\right),i=1..n\tag{29}$$

The outage probability is computed as stated earlier. This Eq. (29) illustrates that the power allocation to CU with respect to different PU has been evaluated and then the minimum power among the calculated set has been allocated to CU.

4.3.3 Power consumption of cognitive transmitter without primary user's interference

The average power consumption of cognitive transmitter when the optimal power is allocated under the peak transmit power, and peak interference power constraints without PU interference is expressed as:

$$E\left[P\left(\hat{g}_{spi}g_{ss}\right)\right]=Ei\left(1,\frac{1}{P_{pk}}\right)-Ei\left(1,\frac{Q_{pki}+1}{P_{pk}(1-\sigma^2)}\right)exp\left(\frac{-\sigma^2log(P_0)}{1-\sigma^2}\right)\tag{30}$$

the average expenditure of CU power when the optimal power is allocated by considering only the peak interference power constraint.

$$E\left[P\left(\hat{g}_{spi}g_{ss}\right)\right]=Q_{pki}exp\left(\frac{-\sigma^2log(P_0)}{1-\sigma^2}\right)\left(-log\left(\frac{1-\sigma^2}{Q_{pk}}+1\right)-Ei\left(\frac{\sigma^2log(P_0)}{1-\sigma^2}\right)\right)\tag{31}$$

5 Simulation results and analysis

In this section, we have presented numerically simulated results of the ergodic capacity and outage capacity with or without the interference of PU-Tx to the CU link of the proposed cognitive radio network model. The performance is analyzed under the average as well as peak interference power constraints. The simulation result of proposed model depicts the significant improvement in the data transmission rate. In

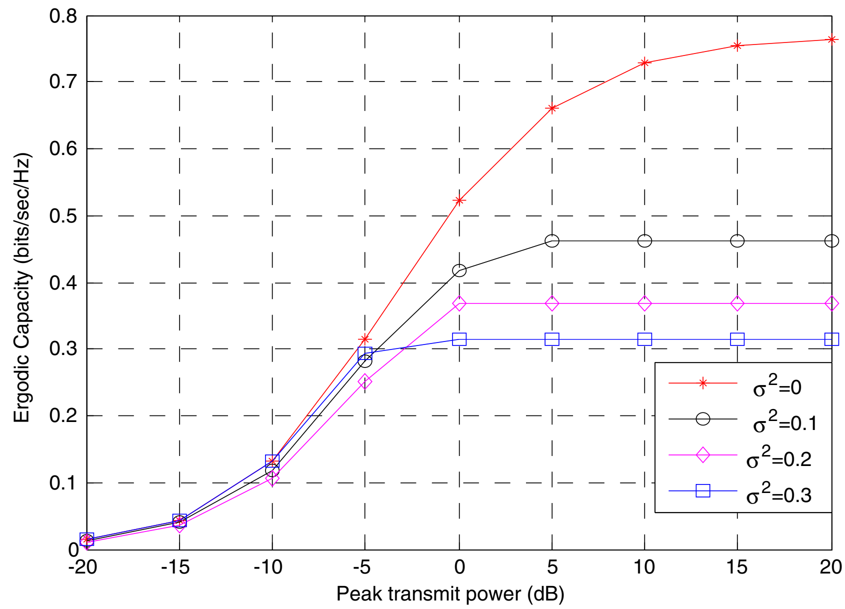


Fig. 2 The response of peak transmit power (dB) on the ergodic capacity (bits/s/Hz) for different values of variance at arbitrary chosen value of the peak interference power (−5 dB)

Fig. 2, the ergodic capacity without PU-Tx interference to the CU link under peak transmit power for different values of the error variance at arbitrary chosen peak interference power (−5 dB) is computed. The numerically simulated result for ergodic capacity of cognitive link with perfect CSI between CU-Tx and PU-Rx is validated with reported literature [11]. However, if the peak transmit power is below the peak interference power then the ergodic capacity for different channel conditions (various values of error variance) increases monotonically and above the peak interference power the ergodic capacity becomes constant gradually as shown in Fig. 2. In addition to this, it is also depicted that with the increase of noise variance, the ergodic capacity reduces in comparison to the perfect channel state information. In Fig. 3, the ergodic capacity is analyzed for different interference outage level with fixed noise variance 0.2. It is also presented that with the increase of interference outage level, the ergodic capacity level rises but when the peak transmit power is greater than that of peak interference power then there is no significant effect of increasing interference outage level.

In addition to this, the average power expenditure of CU-Tx is investigated in Fig. 4 with the peak interference power for different combinations of interference outage level and noise error variance. It is also depicted that there is significantly more power consumption if the interference outage level rises for fixed error variance. On the other hand, if the interference level is fixed then with the increase of noise variance, the average power consumption of the CU decreases.

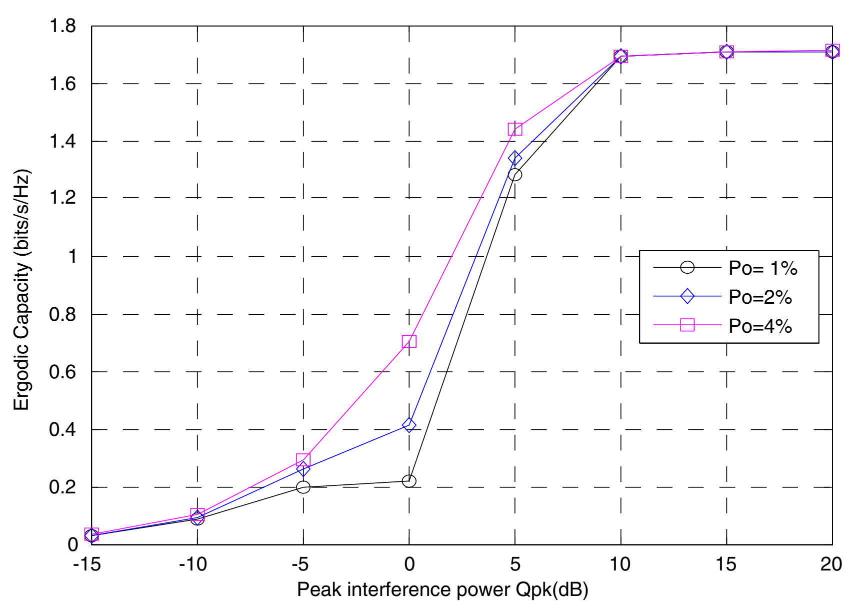


Fig. 3 The response of peak interference power on the ergodic capacity (bits/s/Hz) for different values of the interference outage level at arbitrary chosen value of the peak transmit power (10 dB) and error variance 0.2

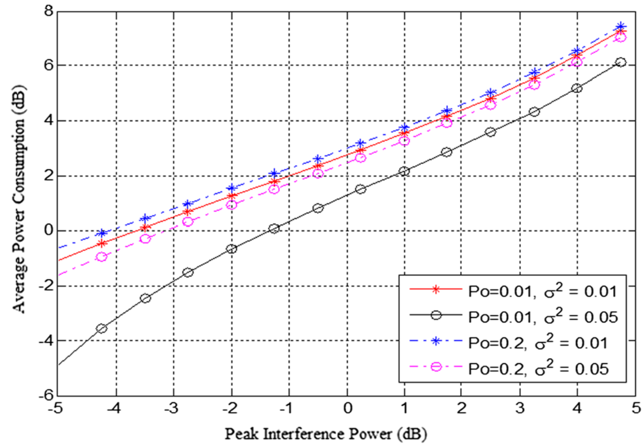


Fig. 4 The average power consumption to achieve ergodic capacity limits of cognitive transmitter with different combination of interference outage level and error variance

Moreover, it reveals that with the increase of interference power constraint, the power consumption of CU-Tx is monotonically increased. The variation of ergodic capacity under the joint peak transmit power and average interference power constraints without consideration of interference of primary user is illustrated in Fig. 5. It has been illustrated that when the peak transmit power is more than the average interference power, there is variation in ergodic capacity with error variance. However, when the peak transmits power becomes less than that of the average interference power, the ergodic capacity for different error variance values remain same. In addition to this, the numerically simulated result of the ergodic capacity with perfect channel state information is validated with literature reported in [11].

Moreover, the comparison of Figs. 2 and 5 reveal that the average interference power constraint is better than that of the peak interference power constraint. The effects of interference of PUs on the ergodic capacity of CU link under the joint peak transmit power and peak interference power for different error variance is illustrated in Fig. 6. It is shown that as the interference of the PU to CU link increases, the ergodic capacity of the CU link decreases. With the comparison of Figs. 2 and 6, it is revealed that there is significant reductions in the ergodic capacity at the peak transmit power, the peak interference power and noise error variance 5 dB,-5 dB and 0.1, respectively. In addition to this it is analyzed that as the number of PUs increase above two then the reliable communication cannot achieve. The variations of outage probability without and with PU interference under the peak transmit power and peak interference power constraint is presented in Figs. 7 and 8a, respectively.

If the PUs interferes with the CU link, the outage probability levels rise. In case of without PU-Tx interference, it has been illustrated that as the peak transmit power is less than that of the peak interference power, the outage probability level remain same for different noise error variance but with the PU interference, the outage probability is constant with different outage probability levels. From Fig. 8a, it is depicted that the

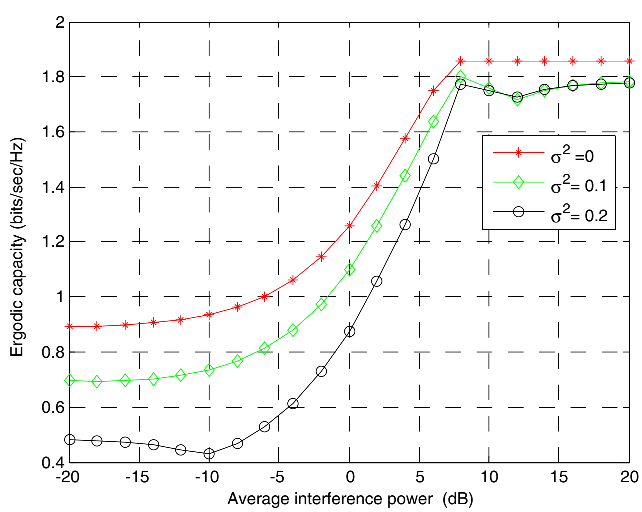
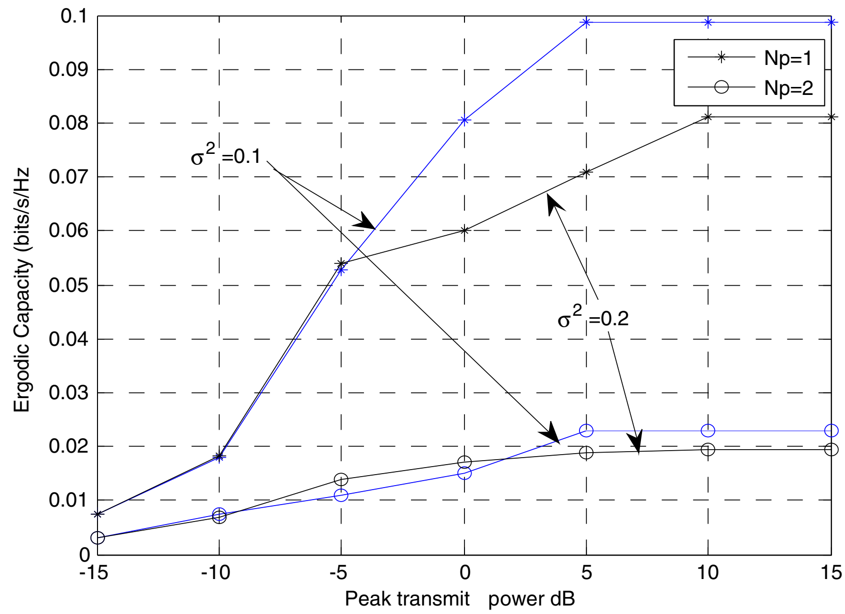


Fig. 5 The response of average interference power (dB) on the ergodic capacity (bits/s/Hz) for different values of variance at arbitrary chosen value of the peak transmit power (5 dB)

Fig. 6 The response of peak transmit power (dB) on the ergodic capacity (bits/s/Hz) of cognitive user link with multiple primary users' interference with arbitrary chosen values of the fixed peak interference power (−5 dB)with fixed noise variance $\sigma^2 = 0.1$ and $\sigma^2 = 0.2$



outage probability increases with the increase of PU's interference. Moreover, it is also analyzed that if the PUs increases above four then the data rate of CU link become very less; therefore, the communication cannot be established efficiently. Figure 8b demonstrated the effect of interference of the PU to the CU link when the transmit power to CU is allocated under the peak interference power constraint only. The comparison between Fig. 8a, b reveals that the outage probabilities under the joint peak transmit power and peak interference power is more in comparison to the individual peak interference power constraint. If the multiple numbers of PUs interfere to the CU link, then the peak interference constraint provides better result.

The consumption of power of CU-Tx under the joint peak transmit power and peak interference power as well as under the peak interference power only is portrayed in Fig. 9. It is exposed that the consumption of power under the joint constraints (the peak transmit power and peak interference power) is very less in comparison to that of the peak interference power constraint only. The average power consumption of CU under the peak interference power constraint only is validated with the reported literature [19]. From Fig. 9, it is clarified that it is significantly much better to allocate power to CU under the joint constraints (the peak transmit power and peak interference power) as compared to the peak interference power constraint only.

Fig. 7 The response of the peak interference power 9(dB) on the outage probability at arbitrary chosen value of the peak transmit power (10 dB) and fixed data transmission rate ($r_0 = 1$ bits/s/Hz) under the peak interference power and the peak transmit power constraint

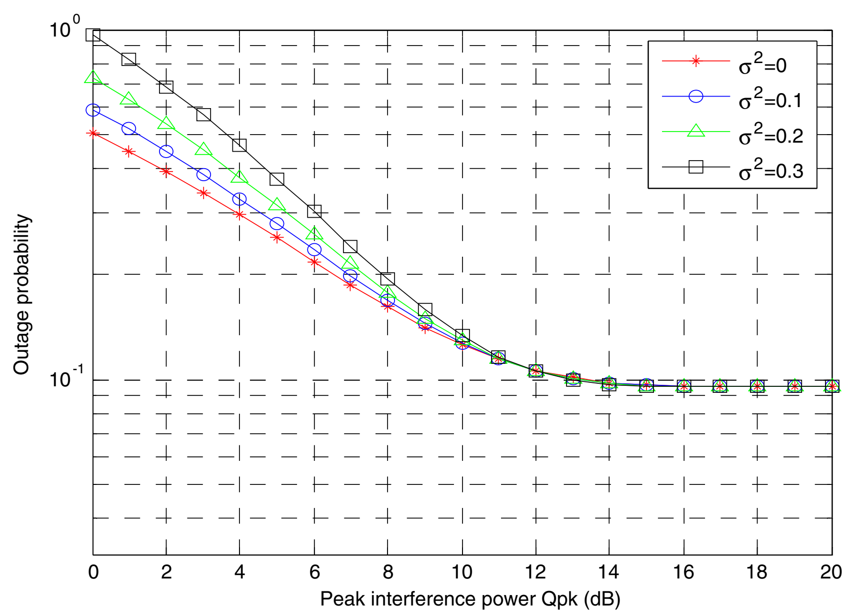
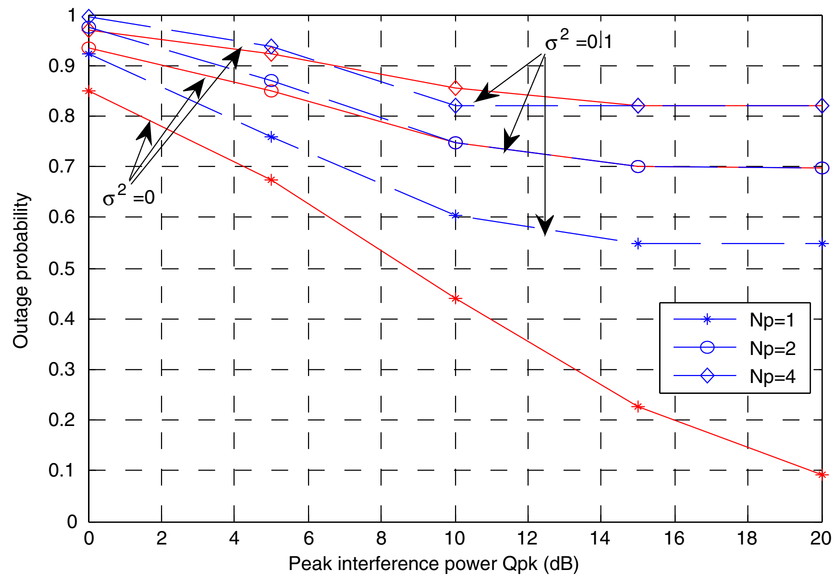
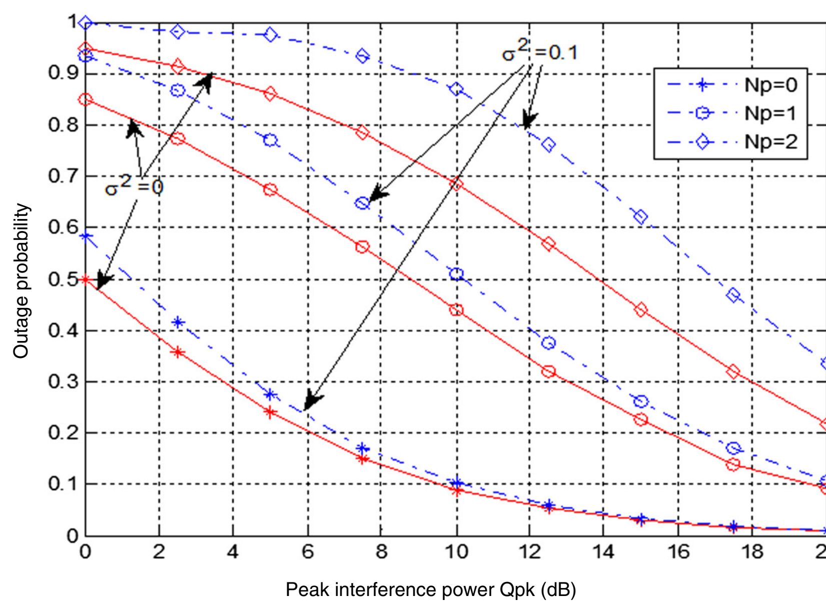


Fig. 8 The outage probability of cognitive user link with multiple primary users' interference with variation in the peak interference power for chosen value of peak transmit power (10 dB) with fixed $\sigma^2 = 0$ and $\sigma^2 = 0.1$ under **a** peak transmit power and peak interference constraints and **b** peak interference only



(a)



(b)

6 Conclusion

In this paper, we have presented the analysis of ergodic capacity and outage probability of the CU link, with and without PU interference. It has been presented that with the numerically increasing value of the noise error variance and interference from the PU to CU link, the ergodic capacity of CU link decreases, and the outage probability increases significantly. The power consumption of CUs under the joint constraint (peak transmit power and peak interference power) is very much less as compared to that of the peak interference power constraint. The capacity limits under the joint peak/average transmit power and average interference power constraint is also very important issue to analyze the proposed system model, which will be reported in the future communication. In practice, the available system parameters (CSI and interference power) to enable power control and beam-forming could be uncertain due to various factors such as estimation error and/or measurement error, thus the robustness of the designed algorithms should be considered in order to overcome the effects of parametric uncertainty. The stochastic Gaussian model includes a mean and variance side information of the fading coefficients at the transmitter. The channel estimation acquired independently by the transmitter may suffer from the channel estimation accuracy due to RF chain impairment, which limit channel estimation reciprocity. In addition to this,

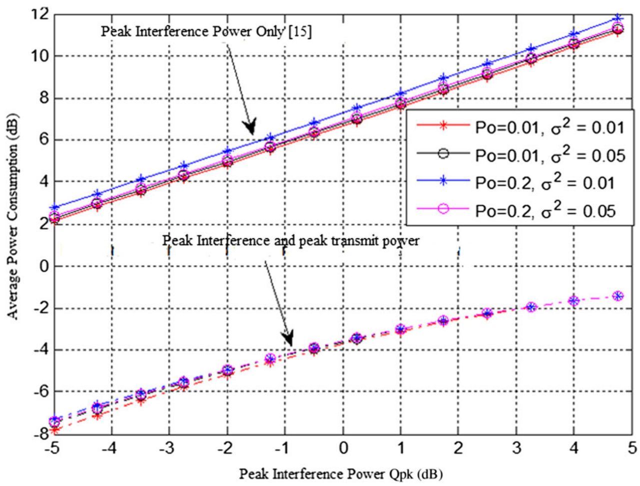


Fig. 9 The average power consumption to achieve outage capacity limit of cognitive user transmitter with different combination of interference outage level and error variance under the peak transmit power and peak interference constraints as well as under the peak interference power constraint only

the causality requires acquiring CSI prior to transmission, while the channel may change when actual transmission takes place. These give rise to the practical stochastic Gaussian model with mean and variance. The practical transmit channel state information model is a stochastic Gaussian model with mean and variance information which is commonly used for modeling the channel estimation error. The extensive numerical results illustrate that the spectral efficiency achieved by secondary user with partial inter-system CSI within a reasonable range of outage probability.

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