Research Article

Power allocation optimization for fading channels in cognitive radio networks

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Abstract
The radio resource allocation in cognitive radio networks is an essential problem where the secondary users (SUs) use the spectrum allocated to primary users (PUs) without causing much interference to PUs. This paper studies optimal power and bandwidth allocation in a cognitive radio network under Rician and Nakagami-m fading channels. The performance metric for the network used is the ergodic-capacity of all the SUs. Further, this paper investigates the optimal power allocation schemes to achieve the primary capacity bounds of a secondary network with Rician and Nakagami-m fading channels. Specifically, the ergodic-capacity is considered. The methodology used involves deriving closed-form results for both Rician and Nakagami-m scenarios. Besides, the peak/average transmit-power constraints at the SUs and the peak/average interference power constraint imposed by the PU. The equations of optimal power allocations are also formulated under peak-power and peak-interference constraints. Further, the analysis is done for a network of SUs. Simulation results depicted with figures and tables show that the optimal power and bandwidth allocation for Rician and Nakagami-m fading channels. The investigation and analysis on optimal power and bandwidth allocation can be used for future reference of resource allocation in the cognitive radio networks over Rician and Nakagami-m fading channels.

1.Introduction
The radio spectrum is turning out to be scarcer with the growing number of spectrum-hungry applications, then again, the report from the federal communications commission uncovered that most of the licensed spectrum is severely underutilized [1]. The difficulty between spectrum scarcity and spectrum underutilization has been managed in cognitive radio networks (CRNs) [2, 3]. Cognitive radio permits unlicensed users or secondary users (SUs) to access licensed spectrum to such an extent that the induced interference to the licensed users or primary users (PUs) is within the acceptable level. In cognitive radio, the SU senses for idle PU bands, and if found, SU may utilize these bands for its own data transmissions. The SU, however, performs spectrum sensing (SS) while transmitting its own to check the return of PU, and if PU has reappeared, SU has to empty the band immediately to maintain a strategic distance from harmful interferences.

Various works have as of late contemplated data theoretic limits for radio resource allocation in CR. The development of maximum ergodic-capacity for the SU to target the optimal power allocation subject to the average-interference-power (AIP) and peak-interference-power (PIP) constraint set by a PU have been shown [4]. It is investigated that the SU outage-capacity, ergodic-capacity, and minimum-rate-capacity and developed the optimal power allocation for the same under both the AIP and PIP constraints from a PU [5]. The ergodic capacity, delay-limited capacity, and outage capacity of an SU are studied in [6]. The literature stated above [3−6], the study shows the system having only one SU and only in Rayleigh fading whereas, we consider a network of SUs and two fading channels. Even though fading channels have been extensively studied in the current literature [7–10]. They fail to address the issues of resource allocation on these fading channels. The study in [11], shows the two-way cognitive radio systems and addressed power allocation issues. However, recent investigation into [12] shows that the cognitive system with multiple SUs with multiple access channel models, where the peak power

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assignment is derived to attain the full sum-ergodic-capacity of the SUs for numerous power constraints. In [13], the author proposed a framework to control the selection of channels and assessed the framework execution of such a CRN. Some of the equations derived from the above stated works [11−13] have been used here and apply the considered channel conditions. The study in [14], shows that Nakagami-m provides better bit error rate performance than Rician. The study in [15] shows that the capacity of Nakagami-m fading channels drastically increases compared to other Rayleigh, Rician and Weibull fading channels. The study in [16], shows the SS uses different methods with known and unknown noise levels. The study carried out for multilevel sensing and power allocation in Rayleigh fading channel have been discussed in [17, 18].

1.1Rician fading
In realistic situations, the movement of the mobile device often results in the mobile to switch from the Line-Of Sight (LOS) path to a Non-Line-Of-Sight (NLOS) path and vice versa. Rician fading channel is a distinctive communication channel model in wireless and mobile systems, such as space, satellite, and naval communication, etc. In certain situations, the LOS component of the signal becomes very feeble. This happens when K-factor of the Rician fading channel is low. Only a few studies can be found on the Rician fading channel with respect to optimum power and bandwidth assignment in CRNs. It is worthwhile to investigate the performance of the sum ergodic capacity with respect to peak transmit power and interference in the Rician fading channel.

1.2Nakagami-m fading
The Nakagami-m channel model was proposed by Nakagami in the early 1940s to depict fast fading in high-frequency channels. This channel model was selected as it is appropriate for experiential data and it is also handy, as it is more flexible and accurate in tallying some empirical data than other fading models. This channel model is most suitable for certain data signals used in metropolitan radio multipath-channels. Here m is the Shape factor of the Nakagami channel model. The various conditions from Rayleigh to Rician can be modeled by the Nakagami distribution; hence it is frequently used in terrestrial communication and satellite communication as a fading model. These interesting characteristics are the reasons for the extensive use of the Nakagami fading model to theoretical and empirical research in radio communication.

2.Materials and methods
2.1System model
The cognitive radio system assumed (*Figure 1*) consists of one or more PUs and N SUs with a relay having multiple sensors. The PUs and the SUs operate in the same spectrum with bandwidth W for their transmissions. Let h_i and g_i denotes the channel gain between secondary transmitter and secondary receiver (SU_{TX}-SU_{RX}) and between secondary transmitter and the primary receiver (SU_{TX}-PU_{RX}) respectively.
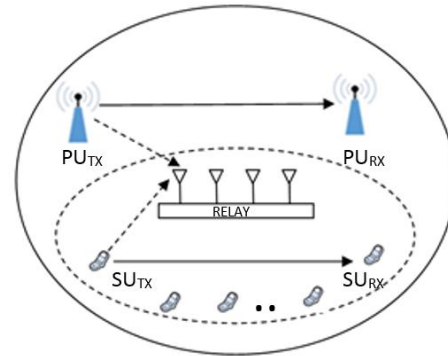

Figure 1 System model

Further let *H* and *G* denote the probability-density-function (PDF) of the two channels discussed above, and let $h \triangleq [h_1, h_2, \ldots \ldots h_N]$ and $g \triangleq [h_1, h_2, \ldots \ldots h_{N,}]$ represents instantaneous channel power gains, all the above parameters are assumed to be known for SUs.

2.2Optimal resource allocation
This paper examines the resource sharing issues for one user. Let us assume that there are *N* channels arranged in decreasing order in accordance with their channel-gain to the interference-noise ratio (CINR) quantified at the recipient. The channels sorted so that, assigned channels *K* can be used to define the start of the channel assignment in place of the binary parameter *x*. B is the bandwidth of each channel, and the PU action indicator is $\omega^{(k)}$ where *k* is the indicator(1 to *N*). This results in the total $K \in \{1, \ldots, N\}$ the number of channels and $p^{(k)} \in \mathcal{R}^+ \{0\}$ the power turns out to be the user power allocation entities to be found so that the data rate constraint ϕ can be fulfilled. The optimization for the resource sharing problem can be articulated as below:

$$\min_{K,p} \{F_B F_P\} : F_B = \sum_{k=1}^{K} B \, \widetilde{\omega}^{(k)},$$
$$F_P = \sum_{k=1}^{K} p^{(k)}, \tag{1}$$
provided

$$\sum_{k=1}^{K} B \, \log \left(1 + \frac{g^{(k)} p^{(k)}}{\eta + \sum_{p \in P} \mathcal{J}_p^{(k)}}\right) \geq \phi \tag{2}$$

The above problem can be solved in two steps. The process begins by determining the power for the given channels K^*, and then determines the peak value of K that minimizes the bandwidth-power product on the application of power.

2.3 Channel allocation

After locating the optimum power values for a given number of assigned channels K, it results in K that minimizes the BP product:

$$\min_K \left\{ \left(\sum_{k=1}^{K} B\, \widetilde{\omega}^{(k)} \right) \left(\sum_{k=1}^{K} \frac{2\frac{\phi}{K^*B}}{\prod_{K*}(h^{(k)})^{1/K^*}} - \frac{1}{h^{(k)}} \right) \right\} \tag{3}$$

Gauss-Newton technique [19] can be applied iteratively to solve the above problem. If it is assumed that $\overline{h}$ is the mean $h^{(k)}$ over all channels $k \in \{1, 2, \dots K\}$, and $\Delta^{(k)}$ is the difference between the instant value of CINR $h^{(k)}$ and its mean $\overline{h}$,

This gives $h^{(k)} = \overline{h} + \Delta^{(k)}$. As a result, Equation 3 becomes:

$$\min_K \left(\sum_{k=1}^{K} \widetilde{\omega}^{(k)} \right) \left(\frac{K 2\frac{\phi}{KB}}{\prod_k \overline{(h} + \Delta^{(k)})^{\frac{1}{K}}} - \sum_{k=1}^{K} \frac{1}{(\overline{h} + \Delta^{(k)}}) \right) \tag{4}$$

for multiple user

$$\min \sum_{j=1}^{|J|} \sum_{k=1}^{K} \left(\frac{B}{1-\omega^{(k)}} x_j^{(k)} \right) \tag{5}$$

subject to

$$\sum_{k \in \overline{\mathcal{K}_j}} x_j^{(k)} = 0, \forall x_j^{(k)} \in \{0, 1\} \tag{5a}$$

$$\sum_{j=1}^{|J_i|} x_j^{(k)} \leq 1, \forall i \in C \tag{5b}$$

$$\sum_{k=1}^{K} B x_j^{(k)} \log \left(1 + \frac{g_j^{(k)} p_j^{*(k)}}{\eta + \sum_{p \in P} \mathcal{J}_{pj}^{(k)}} \right) \geq \phi_j. \tag{6}$$

2.4 Optimal power allocation
2.4.1 Ergodic capacity:

For fading channels, ergodic capacity is defined as the maximum attainable rate averaged on all the fading slabs. The solution to the following optimization problem gives peak power assignment.
Pl: $\max_{p1,p2} E[\sum_{i=1}^{2} r_i]$, $\tag{7}$

That gives,

$$p_1 \geq 0, p_2 \geq 0, \tag{8}$$

$$g_1 p_1 + g_2 p_2 \leq I, \tag{9}$$

Where $E[.]$ represents the statistical probability above all the concerned fading channel gains. This makes it easy to prove that P_1 is a convex-optimization problem. Thus, the duality gap is zero and solving its dual problem is the same as solving the main problem. The Lagrangian of this problem can be given as

$$L(p, \lambda, \gamma) = E[\ln(1 + h_1 p_1) + \ln(1 + h_2 p_2)] + \lambda_1 p_1 + \lambda_2 p_2 - \gamma(g_1 p_1 + g_2 p_2 - I). \tag{10}$$

Here λ and γ are the positive dual variables related to the constrictions. The dual function is $q(\lambda, \gamma) = \max_p L(p, \lambda, \gamma)$. The Lagrange dual problem is then given by:
$$\min_{\lambda \geq 0, \gamma \geq 0} q(\lambda, \gamma)$$

Hence, the optimal solution requires satisfying the Karush-Kuhn-Tucker (KKT) constraints below:

$$p_i \geq 0, \lambda_i \geq 0, \gamma \geq 0, \tag{11}$$

$$g_1 p_1 + g_2 p_2 \leq I, \tag{12}$$

$$\lambda_i p_i = 0, \tag{13}$$

$$\gamma(g_1 p_1 + g_2 p_2 - I) = 0, \tag{14}$$

$$\frac{\partial L(p, \lambda, \beta, \gamma)}{\partial p_i} = \frac{h_i}{1 + h_i p_i} + \lambda_i + \gamma g_i = 0. \tag{15}$$

Solving the above constraints using methods as in [6], the optimal solution is then deduced as

$$p_i^* = \begin{cases} \frac{1}{\gamma g_i} \frac{1}{h_i} , & if\ \frac{1}{\gamma} > \frac{g_i}{h_i}, \\ 0, & if\ \frac{1}{\gamma} < \frac{g_i}{h_i}, \end{cases} \forall i \in \{1, 2\} \tag{16}$$

Where γ is determined by solving
$$g_1 p_1^* + g_2 p_2^* = I.$$

Then we examined that how interference-transmission-ratio (ITR) (the ratio of transmission to interference power) influences the transmission strategy of each transceiver. The analysis with three regions is summarized as follows:

$$p_1^* = \begin{cases} 0 & , R_1 > R_2 + I \\ \frac{1}{2}\left(\frac{I}{g_1} - \frac{1}{h_1} + \frac{R_2}{g_1}\right), & R_2 + I > R_1 > R_2 - I \\ \frac{I}{g_1} & , R_1 < R_2 - I \end{cases} \tag{17}$$

$$p_2^* = \begin{cases} \frac{I}{g_2} & , R_1 > R_2 + I \\ \frac{1}{2}\left(\frac{I}{g_2} - \frac{1}{h_2} + \frac{R_1}{g_2}\right), & R_2 + I > R_1 > R_2 - I \\ 0 & , R_1 < R_2 - I \end{cases} \tag{18}$$

Combining the results obtained under all the cases, the optimal solution strategy for Pl can be summarized above.

It is observed that for a transceiver the interference power constraint (IPC) and ITRs define the optimal transmission strategies. Usually, the transceiver with smaller ITR has the opportunity to transmit.

2.5 Optimal power allocation in Rician fading channels
2.5.1 Rician fading
A Rician fading channel can be defined by two parameters: K and Ω. K is the ratio of the power in the direct path to that in other directions. Ω is the total power $(\Omega = v^2 + 2\sigma^2)$, The received signal is Rice distributed with parameters

$v^2 = \frac{K}{1+K}\Omega$ and $\sigma^2 = \frac{\Omega}{2(1+K)}$

The PDF is given as:
$H(x) =$

$\frac{2(K+1)x}{\Omega}\exp(-K - \frac{(K+1)x^2}{\Omega})I_0(2\sqrt{\frac{K(K+1)}{\Omega}}x)$ (19)

Where $I_0(\cdot)$ is the 0th order revised Bessel function

The CDF $F(n) = 1 - Q_1\left(\frac{v}{\sigma_n}, \frac{n}{\sigma_n}\right)$ (20)

Where Q_1 (.,.) is the Marcum-Q function. With H and G are joint probability-density-function (PDF) of the Rician channel gains

From classical water-filling power assignment problem and its optimal solution as in [19].
$\max_{\{p_i(h,g), \forall h,g\} \in \mathcal{F}'} E_{H,G}\{H(\{p_i(H,G)\})\}$ (21)

A. Optimal power allocation over peak-transmit-power(PTP) and PIP Conditions:
In this case, $\mathcal{F}' = \{$PTP, PIP$\}$ and the optimal value of Equation 29 is denoted as the maximum of $E_{H,G}\{f_1(H,G)\}$ with $f_1(h,g)$ for specific realizations h and g given by

$f_1(h,g) \triangleq \max_{p_i(h,g)} H(\{p_i(h,g)\})$ (22)

s.t. $p_i(h,g) \leq P_i^{pk}, \forall i$ (23)

$\sum_{i=1}^{N} g_i p_i(h,g) \leq Q^{pk}.$ (24)

If the optimal solution of the problem in Equation 22−24 is $\{p_i^*\}$ then there exists k, $1 \leq k \leq N$, such that

$p_{s_i}^* = P_{s_i}^{pk}, \forall i, 1 \leq i \leq k-1, 0$ (25)
$< p_{s_k}^* \leq P_{s_k}^{pk}, and$

$p_{s_i}^* = 0, \forall i, k+1 \leq i \leq N.$ (26)
This gives the structure of the optimal solution for power allocation over the PTP and PIP conditions.

B. Optimal Power Allocation over Average-Transmit-Power (ATP) and PIP Constraints:
Here,
$\mathcal{F}' = \{$ATP, PIP$\}$ and the dual function is given as:
$f_4(\{\lambda_i\}) \triangleq E_{H,G}\{f_4'(H,G)\} + \sum_{i=1}^{N}\lambda_i P_i^{av}$ (27)
Where $\{\lambda_i | 1 \leq i \leq N\}$ are the positive dual variables associated with the ATP conditions. Here $f_4'(h,g)$ is written as
$f_4'(h,g) \triangleq \max H(\{p_i(h,g)\}) - \sum_{i=1}^{N}\lambda_i p_i(h,g)$ (28)
s.t. $\sum_{i=1}^{N} g_i p_i(h,g) \leq Q^{pk}.$ (29)

Denoting the optimal solution of the problem in Equation 28−29 as $\{p_i^*\}$, thus, for the optimal power allocation under the ATP and PIP constraints, there exists at most only two users that transmit at nonzero power.

2.5.2 Nakagami-m fading
PDF equation as shown below:
$f(x; m, \Omega) = \frac{2m^m}{\Gamma(m)\Omega^m} x^{2m-1} \exp\left(-\frac{m}{\Omega}x^2\right), \forall x \geq 0.$
$m \geq 1/2$, and $\Omega > 0$)   (30)
Its cumulative distribution function is
$F(x; m, \Omega) = P(m, \frac{m}{\Omega}x^2)$
The parameters m and Ω are
$m = \frac{E^2[X^2]}{\text{Var}[X^2]}, \qquad \Omega = E[X^2]$

Optimal Power Allocation under PTP and PIP Constraints:
Similar analysis as in A.1 can be performed to find the optimal solution as $\{p_i^*\}$ *then there exists k, $1 \leq k \leq N$,*
such that
$p_{s_i}^* = P_{s_i}^{pk}, \forall i, 1 \leq i \leq k-1, 0 < p_{s_k}^* \leq P_{s_k}^{pk},$ (31)
and $p_{s_i}^* = 0, \forall i, k+1 \leq i \leq N.$ (32)
This gives the structure of the optimal solution for power allocation under the PTP and PIP constraints.

Optimal power allocation under ATP and PIP constraints:
Similar analysis as shown above can be performed to find the optimal solution as $\{p_i^*\}$,

3. Results
This paper considers a cognitive radio network with one PU and a network of SUs. Two separate fading channels the Rician and Nakagami-m are considered. About 1000 randomly generated sets of channel

power gains h and g are used. Other parameters assumed are W=1, σ^2=1.

Figure 2 shows the simulation of the sum ergodic capacity in PTP+PIP, and PTP+AIP constriction against P^{pk}. The simulation is carried out for N=2 and N=4 for Rician fading channel. It can be seen from the figure that the maximum sum ergodic capacity attained in PTP+AIP is higher than that obtained over PTP+PIP for any given number of SUs. This is for the reason that the power assignment is handier for SUs over the ATP constriction than over the PTP constriction. Further achieved maximum ergodic-capacity improves with more number of SUs.
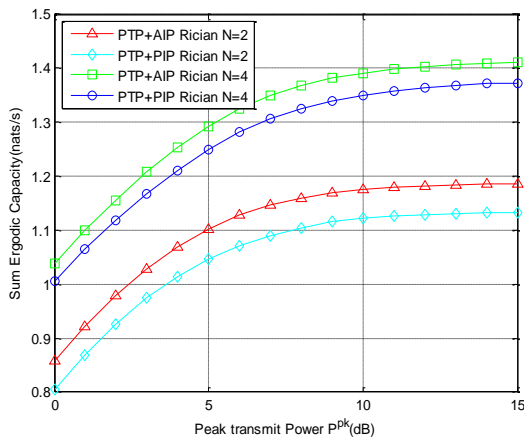

Figure 2 Sum ergodic capacity with Rician fading channel versus P^{pk}

Figure 3 shows the simulation of sum ergodic capacity in PTP+PIP, and PTP+AIP constriction against P^{pk} with Nakagami-m fading channel for N=2 and N=4. The results are more or less similar as in *Figure 2*. However, Nakagami-m channel has better maximum sum ergodic capacity than the Rician channel. Further, it can be observed that the performance of ergodic capacity increases with the number of SUs.
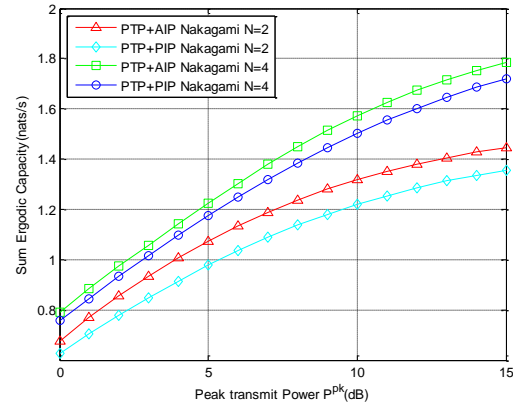

Figure 3 Sum ergodic capacity with Nakagami-m fading channel versus P^{pk}.

Figure 4 shows the plot of sum ergodic capacity in PTP+PIP and ATP+PIP constriction against Q^{pk}. The simulation is carried out for N=2 and N=4 for the Rician fading channel. It can be seen from the figure that the maximum sum ergodic capacity attained in ATP+PIP is higher than that obtained under PTP+PIP for any given number of SUs. This is for the reason that the power assignment is handier for SUs over the ATP constriction than over the PTP constriction. Further achieved maximum ergodic-capacity is better with higher number of SUs.

Figure 5 shows the plot of sum ergodic capacity in PTP+PIP and ATP+PIP constrictions against Q^{pk}. The simulation is carried out for N=2 and N=4 for Nakagami-m fading channel. It can be seen from the figure that the maximum sum ergodic capacity attained in ATP+PIP is higher than that obtained under PTP+PIP for any given number of SUs. This is for the reason that the power assignment is handier for SUs over the ATP constriction than over the PTP constriction. Further achieved maximum ergodic-capacity is better a greater number of SUs. It can also be observed that the Nakagami-m channel has better maximum sum ergodic capacity than Rician channel.
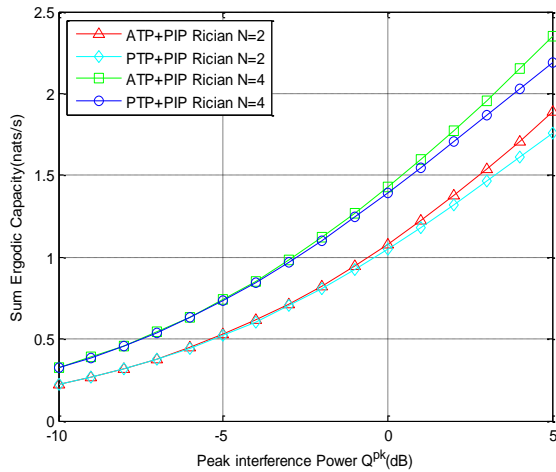
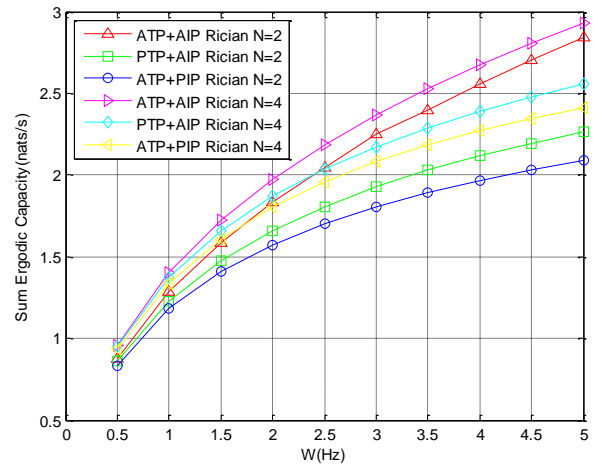**Figure 4** Sum ergodic capacity with Rician fading channel versus Q^{pk}

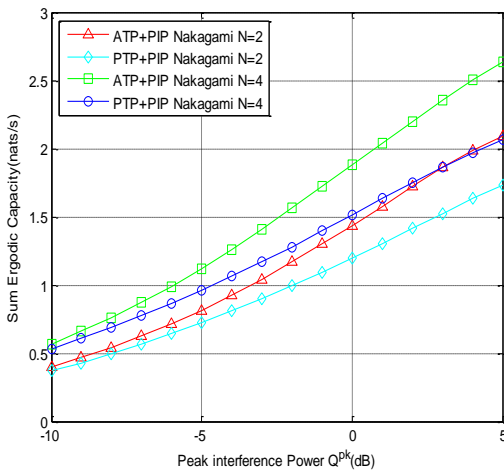**Figure 6** Sum ergodic capacity with Rician fading channel versus W

Figure 5 Sum ergodic capacity with Nakagami-m fading channel versus Q^{pk}
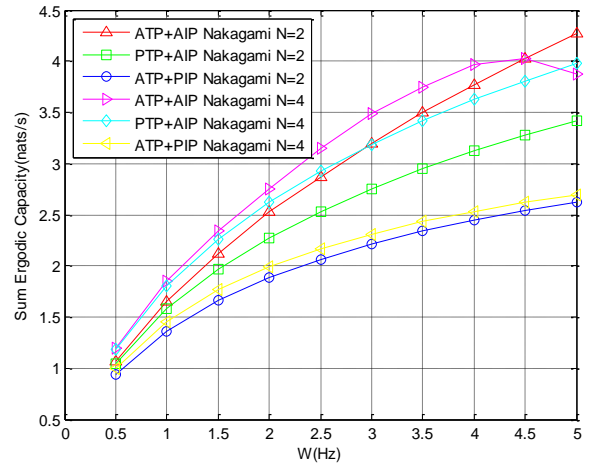

Figure 7 Sum ergodic capacity with Nakagami-m fading channel versus W

Figure 6 shows the plot of maximum sum ergodic capacity in PTP+AIP, ATP+PIP, ATP+AIP versus W for N=2 and N=4 with Rician fading channel. It can be seen that the increase in the number of SUs results in better maximum sum ergodic capacity. Here it can be observed that with the increase in W does not cause saturation in the sum ergodic capacities.

Figure 7 shows the plot of maximum sum ergodic capacity in PTP+AIP, ATP+PIP, ATP+AIP versus spectrum(W) for N=2 and N=4 with Nakagami-m fading channel. It can be observed that the performance remains similar to the earlier plots of Nakagami-m fading channel. Again Nakagami-m channel has better maximum sum ergodic capacity than the Rician channel

4.Discussion

This paper emphasizes on the optimal power allocation in Rician and Nakagami channel fading models in CRNs, where multiple SUs share the licensed spectrum of a PU. The sum ergodic capacity of the SUs, which is a relevant network performance metric for delay-tolerant traffics, is studied.

At first, a framework has been developed for the optimal bandwidth and power assignment for a generalized situation and for a generalized channel fading, the solution for this problem is then extended to the problem associated with Rician and Nakagami channel fading states. Closed-form expressions were developed for both scenarios. Besides the peak/average transmit-power constraints at the SUs and the peak/average interference-power constraint

imposed by the PU. The expressions of peak power allocations are also derived under peak-power and peak-interference conditions.

Most of the literature found deals with optimization of the power and bandwidth allocation in Rayleigh fading model while the work concerns to Rician or Nakagami fading models can be hardly found. In this paper the work has been exclusively carried out for Rician and Nakagami fading models. Further the outcomes of Rician and Nakagami bandwidth and power allocation optimization under different number of SUs are compared.

With respect to *Table 1* and *Table 2* it can be seen that the Nakagami-m channel has better maximum-sum-ergodic capacity than that of the Rician channel. The above result justifies the fact that the slope of the ergodic probability in Nakagami fading is steeper than that in Rician fading. Further, it can be observed that the performance of ergodic capacity increases with the number of SUs.

Table 1 Sum ergodic capacity versus PTP of Rician and Nakagami-m fading channels

PTP (dB)	Rician Sum-ergodic-capacity		Nakagami-m Sum-ergodic-capacity	
	N=2	N=4	N=2	N=4
0.0	0.862	1.143	0.68	0.79
2.5	1.12	1.19	0.88	1.03
5.0	1.11	1.286	1.81	1.23
7.5	1.163	1.361	1.21	1.42
10.0	1.173	1.383	1.33	1.57
12.5	1.181	1.40	1.41	1.72
15.0	1.183	1.413	1.45	1.78

Table 2 Sum ergodic capacity versus PIP of Rician and Nakagami-m fading channels

PIP (dB)	Rician Sum-ergodic-capacity		Nakagami-m Sum-ergodic-capacity	
	N=2	N=4	N=2	N=4
-10.0	0.24	0.36	0.43	0.58
-7.50	0.28	0.51	0.65	0.75
-5.0	0.53	0.73	0.78	1.13
-2.50	0.71	1.08	1.11	1.51
0.0	1.09	1.46	1.45	1.85
2.5	1.51	1.89	1.83	2.32
5.0	1.91	2.37	2.13	2.69

It can be seen from the *Figure 4* and *Figure 5* that the maximum sum ergodic capacity attained in ATP+PIP is higher than that obtained under PTP+PIP for any given number of SUs. This is for the reason that the power assignment is handier for SUs over the ATP constriction than over the PTP constriction.

From *Figure 6* and *Figure 7*(also *Table 1* and *Table 2*), it is clear that the increase in the number of SUs results in better maximum sum ergodic capacity. Further it can be observed the increase in W does not cause saturation in the sum ergodic capacities. Again Nakagami-m channel has better maximum sum ergodic capacity than the Rician channel.

The work carried out clearly comes out with a strategy for optimized power allocation for Rician and Nakagami fading models in CRNs which were

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the main objective of this paper. The investigation and analysis on optimal power and bandwidth allocation can be used for future reference of resource allocation in the CRNs over Rician and Nakagami-m fading channels.

5.Conclusion

The radio resource allocation problem in CRNs, where SUs use the spectrum allocated to PUs has been considered. The sum ergodic capacity of all the SUs is taken as the performance metric of the network. While the literature discussed above focuses only on Rayleigh fading channel, the work carried out formulates the optimal power allocation strategies to achieve the fundamental capacity limits of a secondary network with Rician and Nakagami-m fading channels which is the main objective of this paper. In particular, the ergodic capacity is

considered. Closed-form solutions are obtained for both scenarios. Further the system model considers a network of SUs which is hardly addressed in previous literature. Different peak/average transmitter power constrictions at the SUs and the peak/average interference power constrictions set by the PU are considered. The equations of optimal power allocations are also derived under peak power and peak interference constraints. Simulation results depicted by both figures and tables show that the optimal power and bandwidth allocation for Rician and Nakagami-m fading channels.

Acknowledgment
None.

Conflicts of interest
The authors have no conflicts of interest to declare.

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