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# Traffic Analysis of a Cognitive Radio Network Based on the Concept of Medium Access Probability

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**Abstract**—The performance of a cognitive radio network (CRN) solely depends on how precisely the secondary users can sense the presence or absence of primary users. The incorporation of a spatial false alarm makes deriving the probability of a correct decision a cumbersome task. Previous literature performed this task for the case of a received signal under a Normal probability density function case. In this paper we enhance the previous work, including the impact of carrier frequency, the gain of antennas on both sides, and antenna heights so as to observe the robustness against noise and interference and to make the correct decision of detection. Three small scale fading channels: Rayleigh, Normal, and Weibull were considered to get the real scenario of a CRN in an urban area. The incorporation of a maximal-ratio combining and selection combing with a variation of the number of received antennas have also been studied in order to achieve the correct decision of spectral sensing, so as to serve the cognitive users. Finally, we applied the above concept to a traffic model of the CRN, which we based on a two-dimensional state transition chain.

**Keywords**—Blocking Probability, Fading Channel, Path Loss Model, State Transition Chain, Throughput

## 1. INTRODUCTION

The rapid growth of wireless devices, as well as the advent of a new high data rate wireless application, has led to a dramatic increase in the need for additional bandwidth for wireless services. To fulfill the demand to be available anywhere, anytime, and when needed, the wireless medium has to be exploited. Currently, providing each new service with its own fixed frequency block operates spectrum allotment. The government regulatory agencies have stated that the 'command-and-control' spectrum allocation prohibits unlicensed access to licensed spectrum. Even though much of the spectrum has been allocated, preliminary statistical reports indicate that most of the frequency spectrum is underutilized. Therefore, in order to overcome the imbalance between the increasing demand for spectrum access and the inefficiency in spectrum utilization, a new method has been proposed in [1] for dynamically accessing the assigned spectrum where the spectrum is not in use. Cognitive radio (CR) has paved the way to

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eliminate the dilemma that the spectrum is in short supply for the emerging requirements of wireless services. CR is a key technology that allows unlicensed users (secondary users) to operate in the licensed spectrum band when the spectrum is not in use. This can help to overcome the lack of available spectrums in wireless communication and it can achieve significant improvements in the high data rate services. CR is designed to sense the change in its surrounding and acts accordingly. In this way, the secondary user (SU) can use the spectrum without hampering the primary user (PU). Therefore, spectrum sensing is an indispensable part in the CR system. To access the channel eligibly, spectrum sensing plays an important role in guaranteeing the quality of service (QoS) for both the PU and SU. Therefore, extensive research has been carried out to improve the performance of spectrum sensing. In short, the various spectrum sensing techniques are sorted into the following major categories: energy detection, cyclostationary detection, coherent detection, covariance-based detection, compressed sensing, and cooperative sensing, which were surveyed in [2-7].

To achieve this goal, new dynamic spectrum access policies have been proposed. These allow a PU to lease part of the unused spectrum resources for the SU, as discussed in [6,8,9]. The main functions of CRs are as described below [10].

- Spectrum sensing: detecting the unused spectrum and sharing it without harmful interference with other users.
- Spectrum management: capturing the best available spectrum to meet user communication requirements.
- Spectrum mobility: allowing the radio terminals to operate in the best available frequency band during the transition to better spectrum.
- Spectrum sharing: scheduling and sharing the spectrum in a fair manner.

A fully distributed and scalable cooperative spectrum sensing scheme based on recent advances in consensus algorithms is proposed in [11]. This is where the SUs can maintain coordination based on only local information exchanges without a centralized common receiver. Again a cross-layer design of cognitive radio relay network is proposed in [12], where information guided transmissions at the physical layer and network coding at the network layer are combined together. Here, a common relay is exploited to help the communications between multiple secondary source-destination pairs, which allows for a more efficient use of radio resources, and generates less interference to primary licensees in the network.

Recently, special attention is being given to the spatial false alarm (SFA) problem where a busy PU outside the sensing region can be detected by a SU as being in the transmitting mode inside the sensing region. Therefore, the SU misinterprets it and hereby loses the opportunity to utilize the unused channel. To solve the SFA issue, [13] reveals the cause of this sensing problem using both stochastic geometry and the statistical signal processing principle and presents the related approaches to improve its negative impact. A reliable performance evaluation method that allows the SU to be aware of the real sensing condition is also proposed in this paper. In [14], the author has developed a theory to find a solution for the medium access probability by including the effect of the conventional false alarm (CFA) probability and the SFA probability. The paper explicitly discusses the probability of a correct decision only for the case of a received signal under the Normal distribution of the fading channel.

Again the work of [14] has been enhanced in [15] for the following three small-scale fading channels of the Rayleigh, Rician, and Nakagami-*m* fading channels so as to get the real scenario of the CR network in an urban area. In this paper, the impact of the fading channel parameters and the sensing range on the profile of the probability of the correct decision is also investigated to optimize the performance of the network.

In this paper, we enhanced the work of Han et al. [13] for the following small scale fading channels: Nakagami-*m*, Rayleigh, Normal, Weible, Rayleigh with the maximal-ratio combining (MRC), and Rayleigh with the selection combining distribution method. We did so by considering two popular path loss models: Lee's path loss model and Okumura-Hata path loss model. The main contribution of the paper in a nutshell is that we bring the concept of a SFA and medium access probability (MAP), two popular path loss models (Okumura-Hata and Lee's models) of wireless links, and two-dimensional traffic models all together to evaluate the performance of the CR network. The paper is organized as follows: Section 2 deals with the path loss model and that concept is applied to CRN under SFA, which is the MAP of CR. The above concept is also amalgamated with a two-dimensional traffic model using the Markov chain. Section 3 provides the results that are pertinent to the theoretical analysis of Section 2 and Section 4 concludes the paper.

## 2. SYSTEM MODEL

### 2.1 Path Loss Model

Path loss depends on the frequency of the transmitted signal; the antenna height at both ends; and the location of the received terminal relative to obstacles and reflectors, link distance, etc. There are several path loss models, but in this paper, we only focus on the two models listed below.

#### 2.1.1 The Okumura-Hata model

In 1968, Okumura drew a path-loss curve in the range of 100 to 1,920 MHz. In his model the microcellular area spanned a few kilometers. Masaharu Hata developed an empirical path-loss model based on the measurement of Okumura. This is known as the Okumura-Hata model. The empirical formulation of data provided by the Okumura model is valid for frequencies in the range of 150–1,500 MHz. The basic formula for the Okumura-Hata path loss model is [16]:

$$\gamma_{av}(r) = 10^{-L_{urban}(r)/10}, \tag{1}$$

where $\gamma_{av}$ is the average SNR at the receiving end, $L_{urban}$ is the loss in dB, and $r$ is the distance between the sender and the receiver.

For a large city, the path loss equation found from [17,18] is:

$$L_{urban}(dB) = 69.55 + 26.16(\log f_c) - 13.82(\log h_{BS}) - a(h_{MS}) + (44.9 - 6.55\log h_{BS})\log(r) , \tag{2}$$

where $f_c$ is the frequency of carrier in MHz, $h_{BS}$ and $h_{MS}$ are the heights of the base station (BS) and the mobile station (MS) antennas in meters.

For suburban and rural areas it is:

$$L_m(Suburban)(dB) = L_m(Urban)(dB) - 2[(\log(f_c/28)]^2 - 5.4\ dB\ ,$$
$$L_m(rural)(dB) = L_m(Urban)(dB) - 4.78\{\log(f_c)\}^2 + 18.33\log f_c - 40.94\ dB\ .$$

The function $a(h_{MS})$ for a large city:

$$a(h_{MS}) = \begin{cases} 8.29(\log 1.54 h_{MS})^2 - 1.1\ dB; & for\ f_c \le 300 MHz, \\ 3.2(\log 11.75 h_{MS})^2 - 4.9\ dB; & for\ f_c \ge 300 MHz. \end{cases}$$

For small and medium cities it is:

$$a(h_{MS}) = (1.1\log f_c - 0.7)h_{MS} - (1.56\log f_c - 0.8)\ dB\ . \tag{3}$$

The model is suitable for a distance above 1 km and the model does not support path specific correction.

### 2.1.2 Lee's path loss model

Lee's model can be used to predict area-to-area path loss. The model consists of two parts:

1) Path loss prediction for a specific set of conditions,
2) Adjustment factors for a set of conditions different from the specified one.

The model requires two parameters:

1) Power at 1 mile interception, $P_{ro}$ in dB,
2) Path loss exponent $\gamma$.

In this model, the received power is [19]:

$$P_r = P_{ro}\left(\frac{r}{r_0}\right)^{-r}\left(\frac{f}{f_0}\right)^{-n}\alpha_0\ . \tag{4}$$

In dB, the received power will be:

$$P_r = P_{ro} - 10\gamma\log\left(\frac{r}{r_0}\right) - 10n\log\left(\frac{f}{f_0}\right) + \alpha_0\ , \tag{5}$$

where $n$ is a constant whose value lies in the ranges of 2 to 3, which depends on the geographical location and operational frequency. The parameter $\alpha_0$ is the adjustment factor for a different set of conditions given in [20,21] and is expressed as:

$$\alpha_0 = 20\log(h_{BS}) + 10\log(P_t) + g_1 + g_2 + 10\log(h_{MS}) - 64\ .$$

The variation of an average SNR with distance is [22,23]:

$$\gamma_{av}(r) = \left(\frac{r}{r_0}\right)^{-n} \left(\frac{f}{f_0}\right)^{-3.84} \alpha_{01},$$

where, $\alpha_{01} = 10^{\alpha_0/10}$.

## 2.2 The Medium Access Probability of Cognitive Radio

MAP is a probability where a SU senses no busy PU inside the sensing region. The objective of conventional sensing in CR is to determine the real on-off status of a PU inside the SU's sensing range. The following two hypotheses are obtained by analyzing the received signal: 'PU off, access opportunity is available' or 'PU on, access opportunity is unavailable.' Fig. 1 shows the total coverage and sensing zone of a SU.

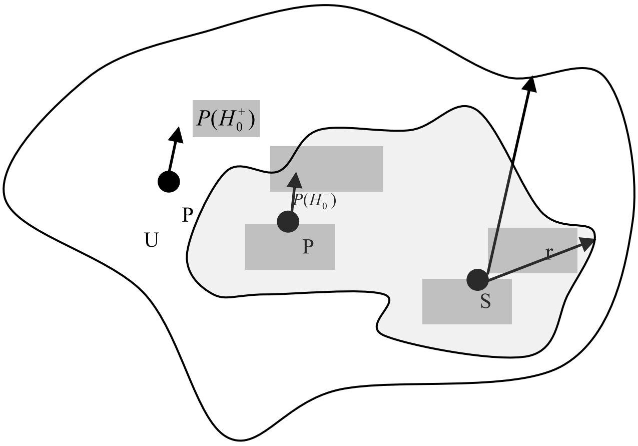

**Fig. 1.** Sensing range of the secondary user and the coverage area of a cell.

To derive the probability of a correct decision, let us introduce the following probabilities [14]:

$P(H_0^-)$ → Probability of a primary user only being at the 'on' state within the sensing region.

$P(H_0^+)$ → Probability of a primary user being at the transmitting state outside the sensing region.

$P(H_1)$ → Probability of a primary user being at the transmitting mode inside the sensing region.

We are now concerned about two cases. In the first case, the PU is only at the 'on' state (not in the transmitting mode) inside the sensing region. In the second case, the PU is in the transmitting mode outside the sensing region.

Let us consider a case when a primary user is only at the 'on' state inside the sensing range. In this case, based on [13], the probability of there being a false alarm will be:

$$P(H_1 \mid H_0^-) = \int_{\varepsilon}^{\infty} f_X(\mu_0, \sigma^2, x)dx, \tag{6}$$

where $x$ is a random variable that indicates the received signal in volts, $\varepsilon$ is the detection threshold, and $f_X(\mu_0, \sigma^2, X)$ is the pdf of the fading channel with the mean and variance of the random variable as the arguments. Considering the Normal probability density function (pdf) in Eq. (6) we can easily obtain by using the idea of [24] as:

$$P(H_1 \mid H_0^-) = Q\left(\frac{\varepsilon - \mu_0}{\sigma}\right). \tag{7}$$

Therefore, the probability of correct decision will be:

$$\begin{aligned} P_{C1} &= P\{\textit{a PU is in non-transmitting mode inside the sensing} \\ &\quad \textit{region}\} \cap P\{\textit{no false alarm received by the SU}\} \\ &= P(H_0^-)\left\{1 - P(H_1 \mid H_0^-)\right\} \\ &= (1-P)\{1 - Q\left(\frac{\varepsilon - \mu_0}{\sigma}\right), \end{aligned} \tag{8}$$

where $P$ is the probability of a PU being in the transmitting mode inside the sensing range. Again, let us consider the case where a PU is in the transmitting mode outside the sensing range. Now, the probability of detecting the PU is:

$$P(H_1 \mid H_0^+) = Q\left(\frac{\varepsilon - \mu_1}{\sigma_1}\right). \tag{9}$$

If $\mu_1$ and $\sigma_1$ are both functions of distance, then:

$$P(H_1 \mid H_0^+) = Q\left(\frac{\varepsilon - \mu_1(r)}{\sigma_1(r)}\right) = P_d(r), \tag{10}$$

which is actually the probability of detecting the PU as if it is in the transmitting mode within the sensing region.

However, the reality is that the PU is outside of the sensing range. Therefore, $P(H_1 \mid H_0^+)$ is another case of there being a probability of a false alarm. To introduce the impact of distance $r$ on $\mu_1$ and $\sigma_1$, we can apply the appropriate pdf of $r$ in the expression of the correct decision.

Let the pdf of distance $r$ from the SU of Fig. 1 be:

$$f_{R'}(r) = \frac{2r}{R^2}. \tag{11}$$

Now the correct decision will be:

$$\begin{aligned} P_{C2} &= P(H_0^+)\{1-P(H_1 \mid H_0^+)\} \\ &= P\int_{r_s}^{R}\{1-P_d(r)\}f_R(r)dr. \end{aligned} \tag{12}$$

By combining the above two probabilities, Eqs. (8) and (12), the total probability of a correct decision, which is called MAP, is expressed as:

$$\begin{aligned} P_C &= P_{C1} + P_{C2} \\ &= (1-P)\left[1-Q\left(\frac{\varepsilon-\mu_0}{\sigma}\right)\right] + P\int_{r_s}^{R}\left[1-P_d(r)\right]f_r(r)\,dr. \end{aligned} \tag{13}$$

Our aim is to determine the MAP for the case of Nakagami-*m*, Rayleigh, Normal, and Weibull fading environment. We will also observe the cases of Rayleigh with MRC and Rayleigh with selection combining schemes. To obtain the results of the above schemes, one has to apply the corresponding pdf in Eq. (6) and the procedures from Eqs. (7)–(13).

## 2.3 Traffic Model

Let us now represent the traffic model of the CRN based on the two-dimensional Markov chain, as shown in Fig. 2. The concept of MAP is included with offered traffic while evaluating the performance of the network. Now, we will link the concept of this MAP with the traffic model of a CR system. Here, we will use the two-dimensional Markov model of M/M/n/n, as shown in Fig. 2, based on the concept of [25-27]. Let the arrival rate of calls of the PU and the SU be $\lambda_P$ and $\lambda_S$ calls per unit time, respectively, with a common termination rate of $\mu$. Some traffic will be lost due to incorrect decisions by the SU's sensor, and therefore, will not get the opportunity of using the network channel.

The actual arrival rate of the SU will be $\lambda_s' = (1-P_f)\lambda_s + P_{md}\lambda_s$ where $P_f$ and $P_{md}$ are the probability of a false alarm and the probability of a misdetection, respectively. In this paper, the above concept will be simplified to: $\lambda_s' = \lambda_s + (1-P_{MA})\lambda_s$.

The state transition chain of Fig. 2 is solved in two steps. In the first step, we determine the generalized solution of any state as:

$$P_{x,y} = \frac{1}{x!\,y!}\left(\frac{\lambda_s'}{\mu}\right)^x\left(\frac{\lambda_p}{\mu}\right)^y = \frac{A_p^x A_s^y}{x!\,y!} \tag{14}$$

which excludes the complete occupied states.

The complete occupied state of the SU, in generalized form, is:

$$P_{x,y} = \frac{(P_{x-1,y} + P_{x-1,y+1})A_p + P_{x,y-1}A_s}{n + A_p}, \tag{15}$$

where, $x + y = n$, $x > 0$ and $y > 0$.

Another two states at the top right and bottom left are:

$$P_{0,n} = \frac{P_{0,n-1}A_p}{n + A_p} \text{ and } P_{n,0} = \frac{(P_{n-1,0} + P_{n-1,1})A_p}{n},$$

respectively, which represents two additional complete occupied states.

The Eqs. (14) and (15) give the probability states before normalization. Hence, we have to evaluate the entire sampling space. The entire sampling space will be the sum of the above states and the blocking probability of SU will be the sum of the complete occupied states in normalized form. The carried traffic of PU and SU will be:

$$\overline{X}_{PU} = (1 - P_{n,0})A_p \tag{16}$$

and

$$\overline{X}_{SU} = \left(1 - \sum_{x=0}^{n} P_{n-x,x}\right)A_s. \tag{17}$$

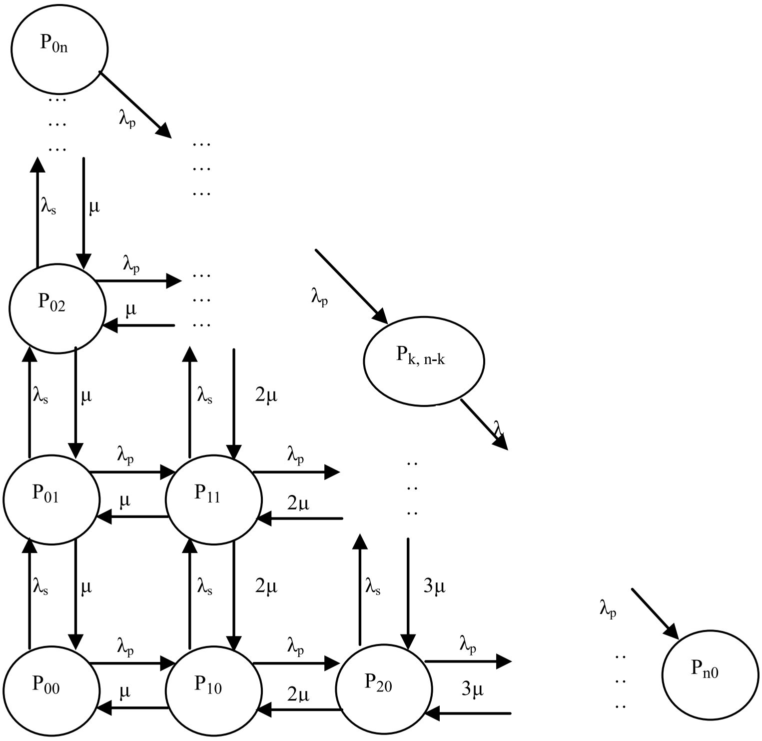

**Fig. 2.** State transition chain of the cognitive radio network.

The lost traffic of SU will be:

$$\overline{L}_{SU} = \sum_{x=0}^{n} P_{n-x,x} A'_s \ , \tag{18}$$

where we have to consider the lost portion of the incorrect decision.

By applying the cut equation to the Markov chain, the sum of the completed occupied states is derived as:

$$C = \sum_{x=1}^{n-1} \left[ \frac{A_p r(x) + A_s \, s(x)}{n + A_p} \right] + \frac{A_p . t}{n + A_p} + \frac{A_p (q + z)}{n} \ , \tag{19}$$

where

$$r(x) = \left[ \frac{A_p{}^{n-x-1}}{(n-x-1)!} \frac{A_s{}^{x}}{x!} + \frac{A_p{}^{n-x-1}}{(n-x-1)!} \frac{A_s{}^{x+1}}{(x+1)!} \right],$$

$$s(x) = \left[ \frac{A_p{}^{r}}{(n-x)!} \frac{A_s{}^{x-1}}{(x-1)!} \right],$$

$$t = \left[ \frac{A_p{}^{0}}{0!} \frac{A_s{}^{n-1}}{(n-1)!} \right] \ ,$$

$$q = \left[ \frac{A_p{}^{n-1}}{(n-1)!} \frac{A_s{}^{0}}{0!} \right],$$

and

$$z = \left[ \frac{A_p{}^{n-1}}{(n-1)!} \frac{A_s{}^{1}}{1!} \right].$$

The entire sampling space is:

$$S = \sum_{i=0}^{n-1} \sum_{j=0}^{n-1-i} \left( \frac{A_p{}^{i}}{i!} \frac{A_s{}^{j}}{j!} \right) + C \ . \tag{20}$$

Therefore, based on [26,28,29], the blocking probability $B_S$ of the SU is obtained as:

$$B_s = \frac{\dfrac{A_p r + A_s s}{n + A_p} + \dfrac{A_p t}{n + A_p} + \dfrac{A_p q + A_p . z}{n}}{S} . \tag{21}$$

The blocking probability of PU will then be:

$$B_p = \frac{\dfrac{A_p (q + z)}{n}}{S} . \tag{22}$$

Now, the throughput of SU in Erlang is:

$$\overline{X}_s = (1 - B_s) \frac{\lambda_s}{\mu} . \tag{23}$$

The lost traffic is:

$$\overline{L}_S = B_s \frac{\lambda_s}{\mu} . \tag{24}$$

Similarly for the case of PU are:

$$\overline{X}_p = (1 - B_p) \frac{\lambda_p}{\mu} . \tag{25}$$

and

$$\overline{L}_p = B_p \frac{\lambda_p}{\mu} . \tag{26}$$

## 3. RESULTS AND DISCUSSIONS

In [15], for each of the fading cases, the authors have chosen two sets of parameters. One is for the case of there being an absence of any PUs and the other is for the case of there being the presence of the PU. In that paper the variation of the medium access probability against the probability of access opportunity is shown taking $\varepsilon = 0.2$ and $r_s = 3$, where it was found that the condition of the network is better for the case when the received signal follows the Normal pdf. For Rayleigh, Rician, and Nakagami-*m* fading channels, the probabilities are very close to each other and each of them rises exponentially. The received SNR was determined by using a simple exponential path loss model.

In our paper, we have considered the two path loss models of Lee's path loss model and the Okumura-Hata path loss model in the case of Nakagami-*m*, Rayleigh, Normal, Weibull, Rayleigh with MRC, and Rayleigh with selection combining schemes. In Lee's path loss model under the Nakagami-*m* fading case, we chose the following fading parameters: $\gamma_{av}$= 0.2, ε = 0.2, $m$ = 6, $p$ = 0.7, $r_s$= 3 km, $n$ = 3, $r_0$= 1.6, $f_0$= 900 MHz, $f$= 2,100 MHz, $h_{BS}$= 300 ft, $h_{MS}$= 10 ft, $P_t$= 55 W. For the Rayleigh fading channel, the only used parameter, $\gamma_{\text{av}}$= 0.2. For the pdf of the Normal distribution, $\sigma$ = 0.2. For the Weibull fading channel, $\alpha$ = 0.22 and $\beta$ = 0.43. Both for Rayleigh with MRC and Rayleigh with the selection combining scheme, $\gamma_{av}$ = 0.2 and the number of received antennas, $N_r$= 2.

Fig. 3 shows the variation of the medium access probability $P_{MA}$ against the probability of the access opportunity $P(H_0)$ *by* taking $\varepsilon$ = 0.2 and $r_s$ = 3 km. In the case of Lee's model, the condition of the network is found to be better for the case when the received signal follows the Rayleigh fading channel. Again, when the access opportunity $P(H_0)$ ranges from 0.4 to 0.6, the $P_{MA}$ for Weibull distribution decreases, but after $P(H_0)$>0.6*,* $P_{MA}$ starts to increase. When the access opportunity $P(H_0)$>0.8, $P_{MA}$ for all the fading cases are almost equal and rises exponentially.

For the Okumura-Hata path loss model, we chose the same parameters as we used in the case of Lee's path loss model, but we got different results than the previous model, as shown in Fig. 4. Here, $P_{MA}$ for all the distributions (Nakagami-*m*, Rayleigh, Normal, Weibull, Rayleigh with MRC, and Rayleigh with selection combining) are very close to each other and follow a linear relation with $P(H_0)$.

In the case of MRC and Selection Combining Schemes, the receiver becomes more sensitive to the received signal. Therefore, there is a possibility of treating a PU in the transmitting state, even though the user is only in the 'on' state. Again, the PU outside the sensing region may be mistreated as if it is staying inside the sensing region.

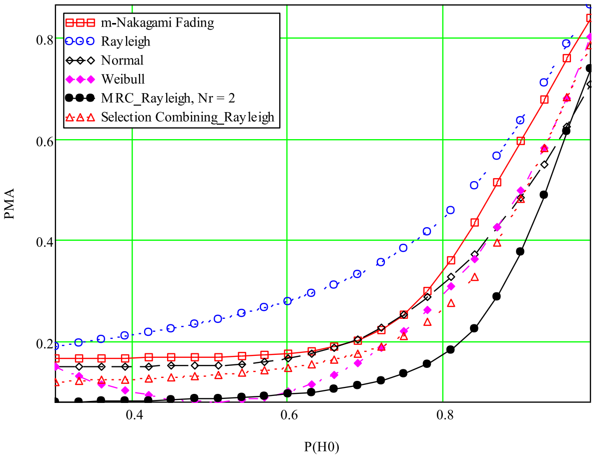

**Fig. 3.** Performance compassion under Lee's model. MRC = maximal-ratio combining.

In both of the above cases, the $P_{MA}$ is reduced considerably, as is visualized in Figs. 3 and 4. Therefore, the multiple input multiple output (MIMO), space time block code (STBC), MRC, or other combining schemes actually deteriorate the $P_{MA}$. However, they do provide promising features for any wireless link. If we incorporate the above schemes, we must use an adaptive algorithm to overcome the deteriorating nature of $P_{MA}$.

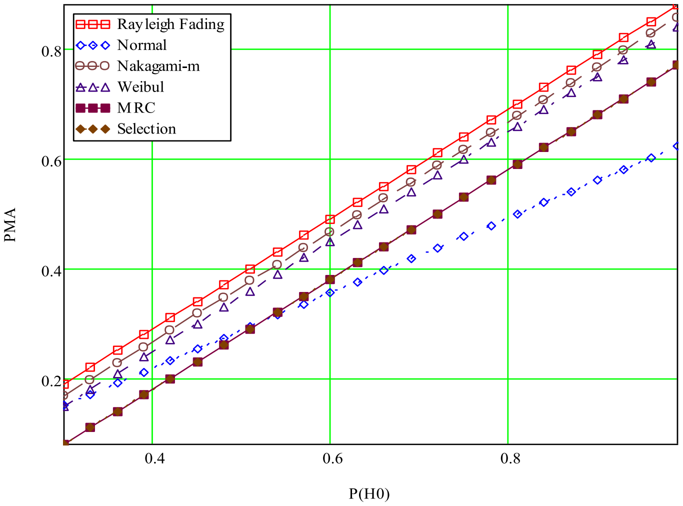

**Fig. 4.** Performance compassion under the Okumura-Hata model. MRC=maximal-ratio combining.

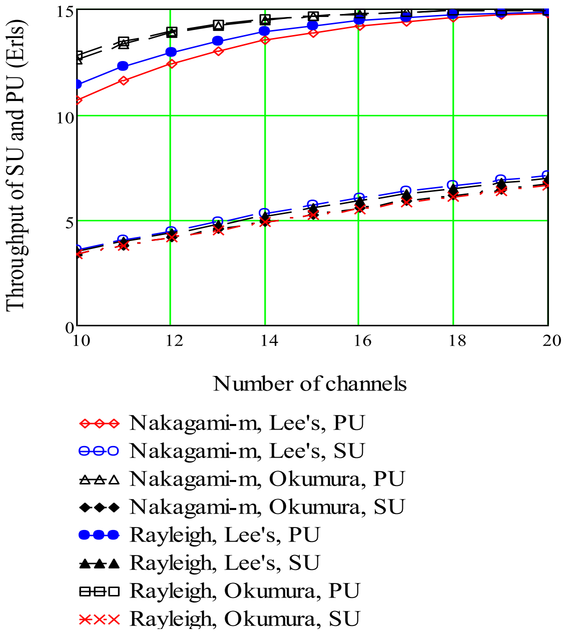

**Fig. 5.** Variation of the throughput of the primary user (PU) and secondary user (SU).

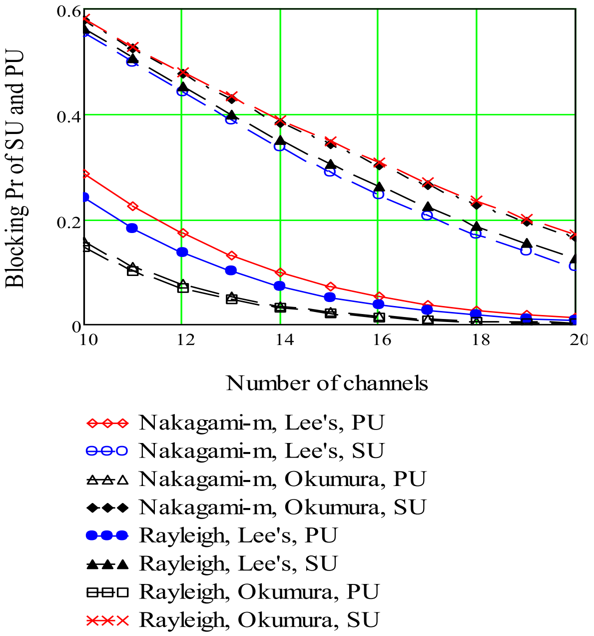

**Fig. 6.** Variation of the blocking probability of primary user (PU) and secondary user (SU).

Now, we will show the impact of $P_{MA}$ on the traffic of the CRN. Fig. 5 depicts the variation of the throughput of the PU and SU against the number of channels of the network under the complete sharing scheme. Here, we consider Lee and Okumura-Hata's models under the Rayleigh and Nakagami-*m* fading cases. The traffic parameters are taken as follows: $A_p$=15 Erls, $A_s$=8 Erls, $P_f$=0.25, $P_{MA}$=0.36 and 0.65 for Lee and Okumura-Hata's model a under the Nakagami-*m* fading cases, respectively; and $P_{MA}$=0.45 and 0.68 for Lee and Okumura-Hata's models under the Rayleigh fading cases, respectively.

The throughput of PU is found to be much higher than the case of SU for all of the fading and path loss models. The Okumura-Hata model reveals a little bit better performance than the case of Lee's model. At the same time, performance is found to be better under the Rayleigh fading case, than that of Nakagami-*m* fading environment. For a larger value of *m* ($m$>5) the performance of the Nakagami-*m* model exceeds the Rayleigh model. Under the same traffic and fading parameters, similar results are found in context of the blocking probability, as shown in Fig. 6. The performance of PU is found to be very sensitive to $P_{MA}$ (i.e., for small increments of $P_{MA}$, the separation between the curves of the PU and SU of Fig. 5 and Fig. 6 increase considerably). Of course the sum of the performances of PU and SU remains fixed.

## 4. CONCLUSION

In this paper, we integrated the path loss model with the detection model of a CR network, based on the concept of a spatial false alarm. The medium access probability and the probability of a false alarm were combined with the offered traffic of the CR network, based on a two-dimensional Markov chain. The main contribution of the paper is that the exact offered traffic (using the above two probabilities), which will obtain the access opportunity of the channels of the CR network, was evaluated. The variation of $P_{MA}$ with $P(H_0)$ from previous literature was enhanced with different path loss models and the corresponding profile was clearly shown. The traffic performance of the primary and the secondary users under different fading and path loss models was also precisely shown.

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