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A slotted ALOHA-based cognitive radio network under capture effect in Rayleigh fading channels

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Abstract: In this paper, a slotted ALOHA-based cognitive radio (CR) network is proposed and the throughput performance of the proposed CR network model under Rayleigh fading channels is examined. Our CR network contains two special groups of users, primary users (PUs) and CR users (CRUs), and they are considered to be sharing a time-slotted-based common communication channel. While PUs can access the channel at any time owing to their legal right, CRUs can only access the channel when it is not occupied by the PUs. In the network model developed, PUs access the channel utilizing time division multiple access as a medium access control technique, and CRUs can access the channel by exploiting slotted ALOHA as a random access scheme when the channel is idle. In the proposed network model additive white Gaussian noise and Rayleigh channels is considered for comparison reasons. Taking capture effect into account in Rayleigh fading channels, we have obtained new equations for the throughput of the proposed CR network. We have also developed, modeled, and simulated a sample networking scenario by using MATLAB with the aim of validating the analytical throughput results. Simulation results of the proposed network model precisely match with the analytical results obtained under different network load conditions. Furthermore, it is shown that the overall channel exploitation is increased by utilizing the spectrum holes without interfering with the PUs' transmissions.

Key words: Capture effect, cognitive radio, fading channels, Rayleigh, slotted ALOHA

1. Introduction

Since the number of wireless users has increased exponentially for the last decade, the spectrum scarcity problem has become a critical issue, mainly caused by fixed spectrum sharing strategies [1]. Cognitive radio (CR) is a new wireless communication technology that aims to improve the spectrum usage. Fundamentally, it gives unlicensed wireless users, also called secondary users or CR users (CRUs), an opportunity to access the unused parts of the spectrum without interfering with the licensed users, also called primary users (PUs) [1,2]. In CR networks, CRUs coexist in the common communication area with the PUs and take advantage of the unutilized portions of the entire spectrum, generally described as spectrum holes [3]. Spectrum holes are generally determined by utilizing numerous signal sensing and detection algorithms [4,5].

In this work, we suggest a slotted ALOHA-based random access CR network and investigate its throughput performance under Rayleigh fading channels. Our proposed network consists of two different kinds of users,

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PUs and CRUs, and they share the time-slotted-based single wireless communication channel. PUs make use of time division multiple access (TDMA) as a medium access scheme and have constantly higher priority to access the channel over CRUs. CRUs utilize slotted ALOHA as a random access technique and access the channel when it is not being exploited by PUs. We put forward new expressions for the throughput of both the CR network and the overall network to analyze the channel utilization while taking the spectrum sensing performance into consideration, i.e. the probability of detection (P_d), and probability of false alarm (P_{fa}). In addition, spectrum sensing time of CRUs and capture effect in fading channels are taken into account in the proposed work. Furthermore, a sample network scenario has been developed, modeled, and simulated with MATLAB to confirm the analytical throughput results. This research also shows that the overall channel utilization may be improved by utilizing the spectrum holes.

The rest of the paper is organized as follows. In Section 2, background information is given and related works are presented. In Section 3, network models of PUs and CRUs as well as a channel model for CRUs are presented. In Section 4, throughput equations of all developed network models are obtained with the purpose of analyzing throughput performances. Numerical results and conclusions are given in Section 5 and Section 6, respectively.

2. Background and related works

In CR networks, determining the spectrum holes is of great importance in order to exploit the channel effectively. By means of spectrum sensing, the binary decision information about the channel usage is obtained and, according to this decision, the channel is exploited by the CRUs. Therefore, in order not to interfere with the PUs, CRUs have spectrum sensing capabilities.

2.1. Spectrum sensing

Spectrum sensing is one of the most important issues of the CR networks as it monitors a given part of the spectrum and makes a binary decision according to the spectrum usage. There are several techniques utilizing various spectrum sensing approaches and the primary transmitted signal detecting based on energy detection is the most commonly used among them owing to its simplicity and not requiring any signal knowledge in advance [6,7].

An energy detection scheme examines the energy in a specified channel and compares the obtained value with a predefined threshold. If the energy level obtained is below the threshold, it is assumed that the spectrum is idle, not used by PUs. In the other case, the spectrum is assumed to be busy, utilized by PUs [8,9]. Therefore, the first case is an opportunity for CRUs to exploit the channel while avoiding interference with PUs [7,10].

In most cases, spectrum sensing can be presumed as the binary hypothesis assessment problem with two potential hypotheses, H_0 and H_1, which represent the nonexistence and the existence of a PU, respectively, given as follows [11,12]:

$$X[m] = \begin{cases} Y[m], & \mathcal{H}_0, \\ S[m] + Y[m], & \mathcal{H}_1 \end{cases}, m = 1, 2, \ldots, N \tag{1}$$

where N is the number of samples, $X[m]$ is a sample received by the CRU, $Y[m]$ follows a Rayleigh distribution with zero mean and variance σ_y^2, and $S[m]$ is the received signal assumed to be an identical and independent random process $(i.i.d.)$ with zero mean and variance σ_s^2. The signal-to-noise ratio (SNR) of the received signal is indicated by $SNR = \sigma_s^2/\sigma_y^2$. Essentially, the decision about the channel usage is denoted as follows [1]:

$$E = \sum_{m=0}^{N} |X[m]|^2 \underset{H_0}{\overset{H_1}{\gtrless}} \gamma \tag{2}$$

where E is the decision statistics, m is the sample index, and γ is a decision threshold formulated as in Eq. (3) [13]:

$$\gamma = 2\sqrt{N}/2\left(Q^{-1}\left(P_{fa}\right) + \sqrt{N}/2\right) \tag{3}$$

where $Q(\cdot)$ is the general Marcum Q-function [12]. P_{fa} is the probability that a CRU incorrectly makes a decision that the specified spectrum is used by a PU when it really is not. P_{dRay}, the probability of detecting a PU signal on a given spectrum when it actually is present, is defined as follows using Eq. (3) [2,5,14]:

$$P_{dRay} = e^{-\frac{\gamma}{2}} \sum_{n=0}^{c-2} \frac{1}{n!}\left(\frac{\gamma}{2}\right)^n + \left[\left(\frac{1+SNR}{SNR}\right)^{c-1} \times \left(e^{-\frac{\gamma}{2\times(1+SNR)}} - e^{-\frac{\gamma}{2}} \sum_{n=0}^{c-2} \frac{1}{n!}\left(\frac{\gamma \times SNR}{2\times(1+SNR)}\right)^n\right)\right] \tag{4}$$

where c is the time bandwidth product. However, calculating the number of samples required according to the SNR in fading channels is weighty owing to its complex structure. Thus, the number of samples necessary to meet the needed P_{dRay} and P_{fa} is obtained under approximation by [13]:

$$N = \left(\frac{Q^{-1}\left(P_{fa}\right)}{-\log\left(P_{dRay}\right)}\right)^2 \left(2\times SNR^{-2}\right) \tag{5}$$

Consequently, τ, the sensing time, is calculated by:

$$\tau = \frac{N}{W} \tag{6}$$

where W is the channel bandwidth [15].

In Figure 1, the spectrum sensing performance of an additive white Gaussian noise (AWGN) channel and Rayleigh fading channel is compared taking missed detection probability and false alarm probability into

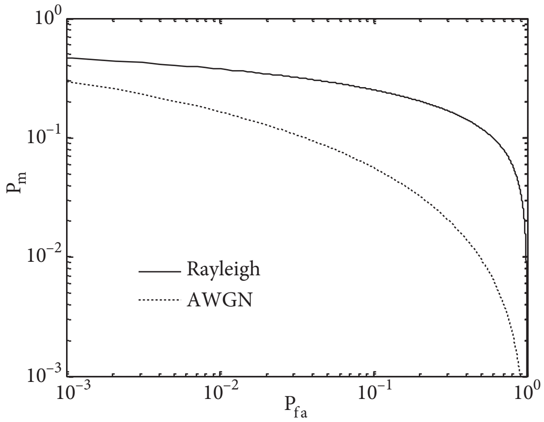

Figure 1. Spectrum sensing in AWGN and Rayleigh channels.

consideration. These two parameters are chosen because the best throughput is achieved when these parameters are low. When the probability of false alarm is 0.05, the throughput of the Rayleigh channel is 20% better than that of AWGN channel.

2.2. Capture effect in packet radio

In wireless environments, packet transmissions may not be successful under harsh fading channels. Nevertheless, a successful packet transmission is possible due to the capture effect in fading channels. Therefore, channel exploitation may be considerably improved by the effects of fading channels [5,9]. For the capture effect, a threshold model is adopted in our CR network model due to its simplicity. According to this model, if a received packet has a power that is more than the capture ratio times the total of the other packets' powers and thermal noise, it captures the receiver and the packet is successfully received [3,5]. Throughout this paper, that packet is labeled as the trial packet. Additionally, thermal noise power is assumed to be insignificant, because it has a very small effect when compared with the interfering signal powers. Accordingly, the capture probability equation is basically described as follows [10]:

$$P_{cap}= P\left[Q_t > z \times (Q_i+Q_n)\right] \tag{7}$$

where Q_t is the power of the trial packet; z is the capture ratio, which is determined according to the modulation, coding, and receiver characteristics; Q_i is the total of all packets' power excluding the trial packet; Q_n is the thermal noise power; and $P[\cdot]$ represents the probability function. Q_t and Q_i are stochastic independent exponential random variables [11].

2.3. Related works

Recently, research works on CR and opportunistic spectrum access have increased dramatically. In addition, a number of CR medium access control (MAC) protocols have also been presented to exploit the spectrum holes of the PUs in nonfading and fading wireless communication channels. In recent times, random access techniques, e.g., slotted ALOHA and carrier sense multiple access, have been used for CR networks with the purpose of utilizing the spectrum holes. In these networks, generally nonfading wireless channels are taken into consideration while evaluating the network performance. However, in order to acquire more realistic performance results, a fading channel must be considered while analyzing the network performance. A new slotted ALOHA-based distributed access CR network was studied in [4]. In that work, a CRU chooses a number of channels for sensing, and if the chosen channel is sensed to be idle, the CRU sends its packet. However, throughput analysis with the packet capture effect in fading environments was neglected. A slotted ALOHA-based multichannel cognitive radio network was suggested in [3]. In that work, throughput and delay analyses with the packet capture effect under Rayleigh fading channels were evaluated, but the author did not consider spectrum sensing time while deriving the network throughput expressions. In [6], the authors suggested carrier sensing-based MAC protocols for CR networks. In that study, CRUs coexist with the PUs in the same communication region, and CRUs adjust their own transmission powers to attain concurrent packet transmission with PUs. The authors also computed throughput and the average packet delay equations for the CR network. It was shown that the suggested technique significantly improves the throughput of the CR network when compared to the common carrier sensing MAC protocols. However, they used nonfading communication channels, disregarding the more realistic fading environments.

3. Network models

In this study, a star CR network topology is considered for both PUs and CRUs. In our network model, PUs and CRUs share the same wireless communication environment, as illustrated in Figure 2. PUs have priority over CRUs when it comes to channel access. Hence, CRUs may only access the communication channel when it is not employed by PUs. There exist N_{PR} PUs and N_{CR} CRUs in the communication environment. PUs exploit TDMA with a constant time period as the MAC technique. CRUs utilize slotted ALOHA as a random access technique to take advantage of the nonoccupied time slots of the primary network.

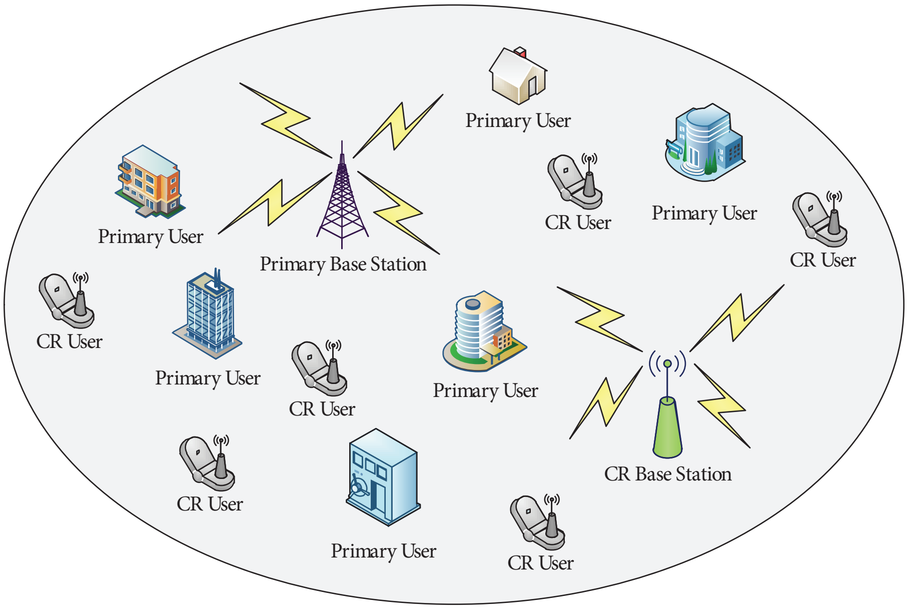

Figure 2. The proposed network model with primary and cognitive radio users and their base stations.

CRUs are assumed to be synchronized with the PUs and detect the licensed channel at the beginning of each time slot to learn if it is busy or idle. If the time slot is idle, then it may be utilized by the CRUs. If the channel is busy, it is assumed that the time slot is employed by one of the PUs and not available for the CRUs' exploitation.

The time slot structure illustrated in Figure 3 is assumed for our network models. In our model, as PUs employ TDMA as a channel access technique, the time axis is separated into fixed-length time slots. As observed from Figure 3, some slots are used by the PUs and the others are not. The time slots employed by the PUs are termed as active; the others not exploited by the PUs are termed as idle. The idle time slots consist of two portions, namely spectrum sensing and data transmission. In the spectrum sensing part, CRUs sense PUs' signals so as not to cause any probable collisions with PUs' packets. In the data transmission part, one of the CRUs may send its packet if it has any. If a CRU decides that the time slot is active, then it carries on to sense the following time slots.

3.1. Primary network model

In the wireless communication region of our network model, there exist N_{PR} PUs and a primary base station. PUs communicate through the primary base station by utilizing a TDMA MAC technique. In the TDMA medium access technique, time is divided into frames and frames are divided into time slots. In the proposed network model, a predetermined time slot is allocated for a PU to transmit its packets. Each PU in a network is assumed to have infinite buffer. The packet transmission time of a PU equals the time slot length. It is also assumed that each PU is a Poisson source with an average packet generation rate of λ_{PR} packets per time slot.

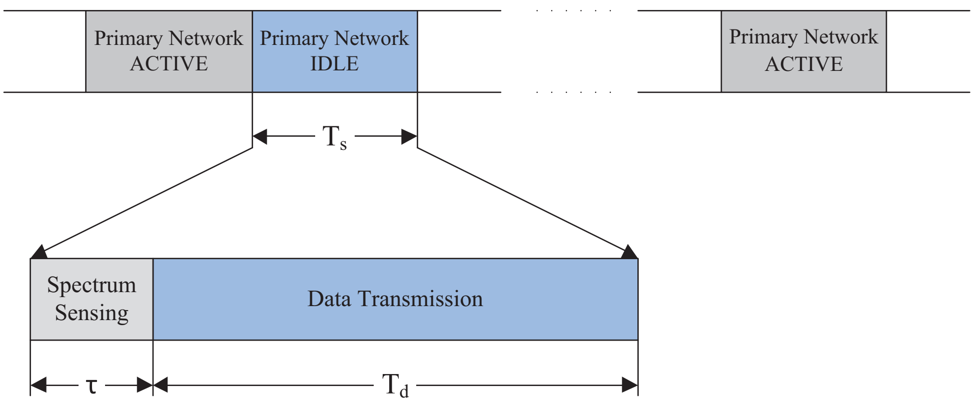

Figure 3. Slot structure of the presented cognitive radio network model.

3.2. CR network model

In the proposed CR network model, a CR base station and N_{CR} CRUs are assumed to be in the same wireless communication area with the PUs. CRUs are uniformly scattered in the communication region and utilize slotted ALOHA as a random access technique. After making a binary decision about the slot utilization at the beginning of each time slot, CRUs send their packets immediately if the present time slot is not employed by PUs. Otherwise, CRUs wait for the availability of the following time slots. In our CR network model, each CRU generates packets according to a Poisson process with an average packet generation rate of λ_{CR} packets per time slot. Moreover, the packet length of PUs is longer than that of CRUs due to the spectrum sensing time.

3.3. Channel model

In our proposed CR network model, we assume Rayleigh fading, which is mostly used in more realistic wireless communication channels [5]. The received power of the packet under Rayleigh fading follows an exponential distribution [7]. The instant power of the received packet, q_s, can be indicated as follows [8,9]:

$$P_Q\left(q_s\right) = \frac{1}{Q_s} \times e^{-\frac{q_s}{Q_s}} \tag{8}$$

where Q_s is the mean received power. Since a perfect power control mechanism [10] is adopted in our model, all the packets are considered to be received with equal mean power at the CR base station. For that reason, each and every CRU regulates its transmission power according to the mean power so as to get rid of the near-far effect, which happens when the received powers of the CRUs close to the base station overpower the received powers of the CRUs far away from the base station [5,8].

We have utilized MATLAB software to develop, model, and simulate the proposed network scenarios. In our proposed simulation model, there exist 20 PUs and 20 CRUs uniformly distributed in the wireless communication area. A Rayleigh fading channel is employed as a channel model. The simulation parameters used are presented in the Table.

Table. Spectrum sensing in AWGN and Rayleigh channels.

Parameter	Value
TDMA time slot length	100 ms
Number of PUs	20
Number of CRUs	20
Frequency of the PUs and CRUs	2.4 GHz
Bandwidth of the PUs and CRUs	6 MHz
Modulation scheme	QPSK
Mean transmitter power for CRUs	100 mW
Probability of detection	0.95
Probability of false alarm	0.01

4. Performance evaluation

4.1. Throughput performance of primary network

We evaluated both primary and CR network performances by means of throughput. In our network models, throughput is defined as the average number of packets successfully received by the base station in a given period of time. The number of packets presented to the network within a given period of time is described as the mean offered load. TDMA packets offered to the network do not collide with one another owing to the fact that TDMA is a contention-free MAC technique. Therefore, when the offered load is equal to or greater than 1, the throughput is equal to almost 1, and when the offered load is less than 1, the throughput equals the offered load. On the other hand, it is possible that PUs' packets may have a collision with those of CRUs owing to the probability of missed detection caused by the CRUs. As a result of this condition, the throughput of the primary network is slightly reduced. Accordingly, the throughput expression for the primary network is given by [2,16]:

$$S_{PR}=\begin{cases} G_{PR}\times(1-P_m), & G_{PR}<1 \\ (1-P_m), & G_{PR}\geq 1 \end{cases} \tag{9}$$

where P_m, which represents the probability of missed detections, is described as $1-P_{dRay}$. S_{PR}, and G_{PR} are the throughput of the primary network and primary network offered load, correspondingly.

4.2. Throughput performance of CR network

In this work, the slotted ALOHA random access technique is exploited by CRUs to utilize the spectrum holes of the PUs. The throughput performance of slotted ALOHA is expressed as the number of packets received by the base station during a given time [15]. For that reason, throughput of CRUs is calculated as follows:

$$S_{CR}=P_{idle}\times G_{CR}\times P_{cap}(z) \tag{10}$$

where S_{CR} is the CR network throughput, and P_{idle} is the probability of PUs being inactive. We assume that G_{CR} is the total offered load presented to the CR network in a given time. Since packets are generated according to the Poisson process, the probability of a trial packet overlapped by n other packets is expressed by [12]:

$$P_n=\frac{G_{CR}^{n}\times e^{-G_{CR}}}{n!} \tag{11}$$

where G_{CR} is the average load presented to CRUs.

To facilitate describing the probability of capturing the trial packet, the condition in which the trial packet is destroyed in the collision must be considered. This condition only happens when $z > Q_t/Q_i$. Since it does not seem probable to calculate the capture probability only with P_{cap} and P_n, the failure probability of the trial packet is taken into consideration in Eq. (12) [5,9].

$$1-P_{cap}\cong P\left[z > \frac{Q_t}{Q_i}\right] \tag{12}$$

Owing to the simplicity of the approach, first the probability of not capturing the trial packet is acquired. Thus, the capture probability is derived as [5]:

$$P_{cap}\left(z\right) = 1\sum_{n=1}^{\infty} P_n \times P\left[z > \frac{Q_t}{Q_i}\right] \tag{13}$$

where $P_{cap}\left(\cdot\right)$ is a function of capture probability.

Using the abovementioned failure probability of the trial packet, the following distribution function is acquired and made simpler by considering the incoherent addition of interfering signals [5,9,12]:

$$P\left[z > \frac{Q_t}{Q_i}\right] = \int_0^z n\times\left(z_0+1\right)^{-n-1} dz \tag{14}$$

The integration expressed in Eq. (14) can then be obtained as follows:

$$P\left[z > \frac{Q_t}{Q_i}\right] = 1\left(z+1\right)^{-n} \tag{15}$$

By exchanging P_n and $P\left[z > Q_t/Q_n\right]$ with Eqs. (11) and (15), the capture probability function is expressed as below:

$$P_{cap}\left(z\right) = 1\sum_{n=1}^{\infty} \frac{G_{CR}^{n}\times e^{-G_{CR}}}{n!}\left(1\left(z+1\right)^{-n}\right) \tag{16}$$

Finally, we calculate the CR network throughput expression with capture effect under Rayleigh fading channels in this way:

$$S_{CR}=P_{idle}\times G_{CR}\times\left(e^{\frac{z\times\left(-G_{CR}\right)}{z+1}}\right) \tag{17}$$

In our work, a specified period of the time is employed for spectrum sensing at the beginning of each time slot. Therefore, we express the channel utilization as the ratio of data transmission time over total time slot duration:

$$\mu = \frac{T_d}{T_s} = \frac{T_s - \tau}{T_s} \tag{18}$$

We also define the effective network throughput as the period of time in which the packet transmission is completed on the channel. It can be given as:

$$S_{CR,eff} = \mu\times P_{idle}\times G_{CR}\left(e^{\frac{z\times\left(-G_{CR}\right)}{z+1}}\right) \tag{19}$$

4.3. Throughput performance of overall network

In terms of total offered load, the overall throughput of the proposed network is denoted as the total throughput of both primary and CR networks. Therefore, the overall network throughput can be calculated as follows:

$$S_T = S_{PR} + S_{CR} \tag{20}$$

where S_T is the overall network throughput. As a result, the throughput of the overall network is written as in Eq. (21), provided that offered loads of the primary and CR networks are equal:

$$S_T = \begin{cases} G_{PR} \times (1 - P_m) + \mu \times P_{idle} \times G_{CR} \times \left(e^{\frac{z \times (-G_{CR})}{z+1}} \right), & G_{PR} < 1 \\ (1 - P_m), & G_{PR} \geq 1 \end{cases} \tag{21}$$

5. Numerical results

The proposed primary network throughput is illustrated for different offered loads in Figure 4. In the networking scenario, there exist 20 PUs, and 20 CRUs, and an infinite first-in-first-out ($FIFO$) buffer is assumed for each PU.

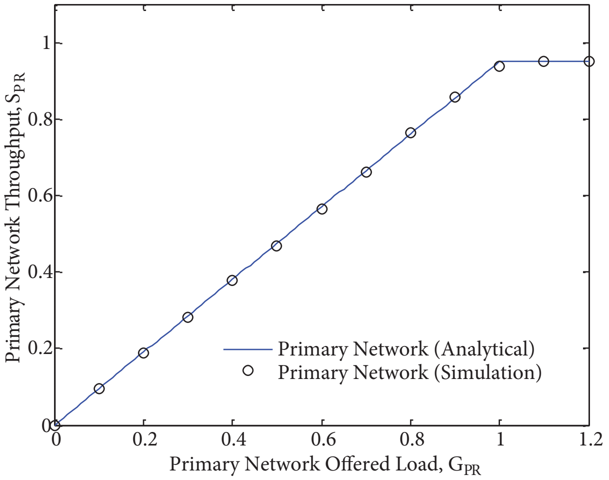

Figure 4. The proposed primary network throughput.

Since missed detections cause very little effect on the throughput performance, as the primary network offered load is enhanced from 0 to 1, so is the primary network throughput at approximately the same rate. However, when the offered primary network load is 1 or greater, the network throughput becomes just about 1. It is clearly observed from Figure 4 that our analytical outcomes match the simulation results obtained.

The CR network throughputs with and without capture effect and for different capture ratios are demonstrated in Figure 5. In the proposed simulation scenario, the number of PUs (i.e. 20) is equal to the number of CRUs. Considering the fact that the capture effect has a substantial effect in wireless fading channels, the CR network throughput lacking capture effect has lower outcomes than the throughput with capture effect.

It can be deduced from Figure 5 that the throughput of the presented CR network decreases as the capture ratio enhances. In other words, the lower the capture ratio, the higher the CR network throughput. The presented analytical results are confirmed by means of a detailed simulation study realized by using MATLAB software (www.mathworks.com/products/matlab/).

In Figure 6, both the primary and the overall network throughputs for different offered loads of primary and CR networks are illustrated.

It is clearly observed from Figure 6 that the overall channel usage of the network has been improved by CRUs exploiting the spectrum holes. It is also revealed that when the offered load of the primary network is low, i.e. between 0 and 0.6 packets/slot, and the CR network offered load is high, channel utilization of the presented network is relatively high.

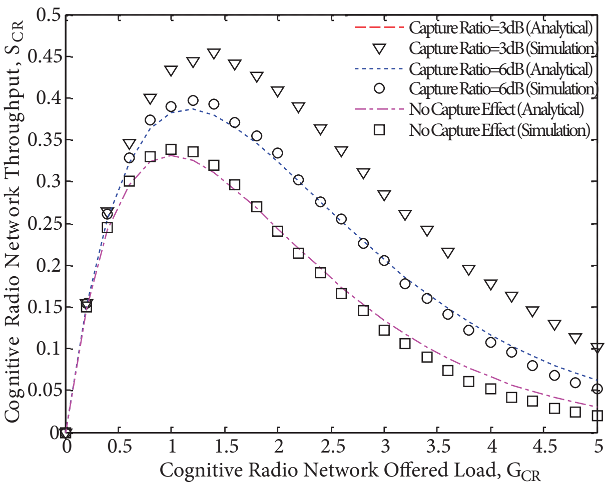

Figure 5. The proposed CR network throughput when $P_{idle} = 0.9$.

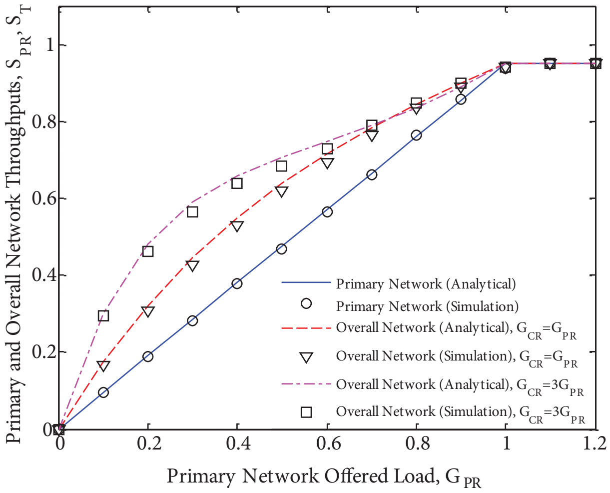

Figure 6. Primary and overall network throughputs when capture ratio is 3.

In Figure 7, overall network throughputs for AWGN and Rayleigh channels are shown for comparison purposes. While the obtaining AWGN channel throughput, the value of P_{idle} is chosen as 0.8. In addition, the capture ratio for the Rayleigh fading channel is considered to be 3. In this figure, the mean offered loads presented to the CR and primary networks are assumed to be same. The throughput performance obtained in Rayleigh fading channels with capture effect is shown to be relatively high when compared to the throughput in the AWGN channel. It is also shown from the figure that the obtained simulation results confirm the analytical model results.

In Figure 8, a comparison of AWGN and Rayleigh channels for various offered loads is demonstrated. While obtaining these results, it is assumed that the CR network has three times more load than the primary network. As also seen in this figure, the Rayleigh fading channel with capture effect has better results than the AWGN channel.

When the offered load is between 0 and 0.1, almost the same throughputs for both channels are obtained. When the offered load is increased, the throughput with the Rayleigh fading channel is higher than the throughput of the AWGN channel.

On the condition that the offered loads of the primary and CR networks are equal, overall network throughput is improved by nearly 11% in the Rayleigh channel. In addition, when the offered load of the CR network is three times more than the offered load of the primary network, the throughput under the Rayleigh channel is improved by almost 16% over the throughput under the AWGN channel. In our study, different than similar works in this area, spectrum sensing time is also considered while calculating effective throughput.

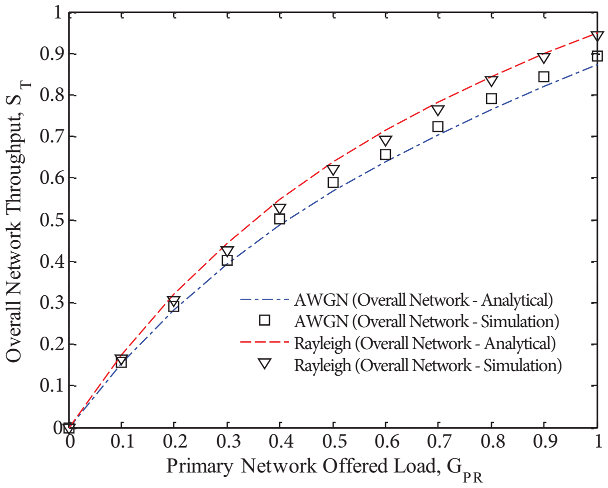

Figure 7. Overall network throughputs when $G_CR = G_PR$.

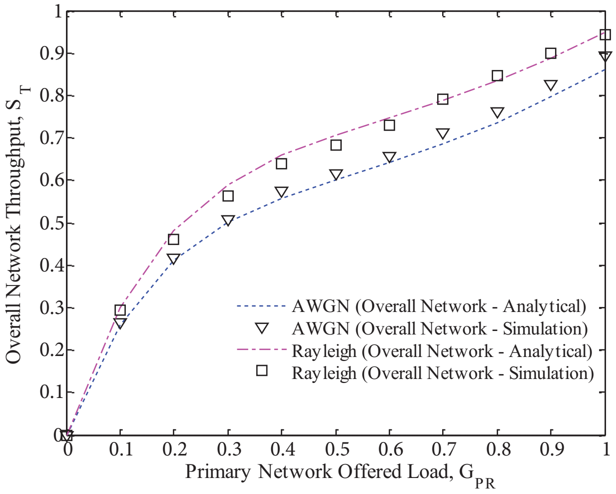

Figure 8. Overall network throughputs when $G_CR = 3G_PR$.

6. Conclusions

In this work, we have investigated a slotted ALOHA-based random access CR network and examined its throughput performance. A time-slotted-based common communication channel is utilized by both PUs and CRUs. PUs access the wireless channel utilizing a TDMA MAC technique. CRUs exploit slotted ALOHA as a random access technique and access the channel when it is not utilized by PUs. New equations for the throughput of both CR and the overall network under Rayleigh fading channels have been provided to assess the overall channel usage considering spectrum sensing time and capture effect. Moreover, an example networking scenario has been developed, modeled, and simulated by utilizing MATLAB with the purpose of validating the analytical results. The results have demonstrated that the overall channel usage of the network can be improved by exploiting the spectrum holes, evading any interference with the PUs' communications.

When the primary and CR networks have the same loads, the total throughput of the network is increased by 11% in the Rayleigh channel. When the CR network has three times more load than the primary network, the Rayleigh channel throughput is increased by about 16% over the AWGN channel.

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