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Abstract: In this paper, a slotted Aloha based cognitive radio (CR) network that consists of two classes of users, primary users (PUs) and CR users is considered and its throughput performance is evaluated. PUs and CR users share the time slotted based common communication channel. PUs are authorized to access the channel and utilize Time Division Multiple Access (TDMA) as a Medium Access Control (MAC) technique. CR users employ slotted Aloha as a random access scheme and can access the channel when it is not occupied by the PUs. We have derived new expressions for the throughput of both CR network and overall network to evaluate the channel utilization. In addition, an example network scenario has been developed, modeled and simulated by using the OPNET Modeler simulation software with the aim of verifying the analytical throughput results. The simulation results obtained under various network load conditions are precisely match with the analytical results. This study has also shown that the overall channel utilization can be improved by well exploiting the spectrum holes without interfering with the PUs’ transmissions.

1. INTRODUCTION

Over the last several decades, wireless communications systems have been taking much attention due to the ever-increasing usage of wireless products and services. As the number of wireless users increase exponentially, spectrum scarcity problem has arisen due to the static spectrum allocation strategies [1]. CR is a new wireless network paradigm that aims to increase the spectrum utilization. Fundamentally, it provides unlicensed wireless users an opportunity to access the unoccupied portions of the spectrum while preventing any interference to the licensed users named also as primary users. In CR networks, opportunistic users called also as CR users coexist in the same communication area within the PUs and exploit the unused portions defined as spectrum holes of the entire spectrum [2], [3].

There are a number of researches about how CR users opportunistically access and exploit the spectrum holes. Recently, many CR MAC protocols have been proposed to exploit the spectrum holes of the PUs. In [3], slotted Aloha is utilized by CR users to exploit the idle time slots of PUs. In this work, spectrum sensing time was not taken into account while calculating CR network throughput. In [4], an infinite population slotted Aloha based CR network was proposed. In this work, CR users share the licensed multi-channel spectrum opportunistically. Two different MAC schemes were introduced and their throughput analysis with the packet capture effect in Rayleigh fading were presented. However, they did not draw on spectrum sensing time while deriving the CR network throughput equations. Carrier sensing based MAC protocols were proposed in [5]. In this work, CR users coexist with the PUs and adjust their transmission power to provide simultaneous packet transmission with them. Throughput and the average packet delay expressions for the CR network are also derived in this work. It is also shown that proposed scheme significantly increases the throughput of the CR network as compared with that of the conventional carrier sensing MAC protocols.

In our work, we have proposed a slotted Aloha based random access CR network and investigated its throughput performance. Our proposed network consists of two classes of users, PUs and CR users and they share the time slotted based common communication channel. PUs utilize TDMA as a MAC technique and have always higher priority to access the channel over CR users. CR users employ slotted Aloha as a random access scheme and can access the channel when it is not used by the PUs. We have derived new expressions for the throughput of both CR network and overall network to evaluate the channel utilization while taking into account the spectrum sensing performance metrics, i.e. probability of detection ($P_d$) and probability of false alarm ($P_{fa}$). In addition, an example network scenario has been developed, modeled and simulated by using the OPNET Modeler simulation software to verify the analytical throughput results. This work has also shown that the overall channel utilization can be improved by well exploiting the spectrum holes without interfering to the PUs’ transmissions.

The rest of the paper is organized as follows. In section II, network models of PUs and CR users are presented and spectrum sensing for CR users is explained in detail. In section III, throughput equations of all network models are obtained in order to evaluate throughput performances. Numerical results and conclusions are presented in section IV and section V, respectively.
2. NETWORK MODELS

In this paper, a centralized CR network where primary and CR users are employed in the same geographical area illustrated in Figure 1 is considered. While PUs are licensed to access to the channel, CR users access to the channel opportunistically when it is not used by the PUs. There are \( N_{PB} \) and \( N_{CR} \) primary and CR users in the networking area, respectively. PUs utilize TDMA with constant time duration as MAC scheme. CR users exploit slotted Aloha as random access scheme to get hold of the idle time slots of the PUs. CR users are precisely synchronized with the PUs and detect the licensed channel at the beginning of each time slot to learn if it is active or idle. If the time slot is idle, then it can be utilized by the CR users. If the channel is active, it means the time slot is occupied by a PU and not available for the CR users’ exploitation.

Figure 1. The proposed cognitive radio network model.

The time slot structure of the proposed network model is shown in Figure 2. Since TDMA is used as a channel access scheme for PUs, time axis is divided into fixed size time slots. The time slots used by the PUs are called active; the others not used by the PUs are called idle. The SU’s time slot when the PUs are idle is composed of two parts namely as spectrum sensing and data transmission. In the spectrum sensing period, CR users detect PUs’ signal in order to avoid probable collisions with PUs’ packets. In data transmission period, after making a binary decision about the PUs’ absence, a CR user sends its packet. If a CR user decides that the time slot is active, then it continues to sense the following time slots.

Figure 2. Slot structure of the proposed cognitive radio network model.

2.1 Primary Network Model

Our primary network model consists of \( N_{PB} \) PUs and one primary base station in the communication area. PUs communicate through primary base station utilizing TDMA MAC scheme. In TDMA medium access scheme, time is divided into frames and frames are divided into time slots. In our model, it is assumed that the number of time slots in a frame equals to the number of PUs. Therefore, a distinct time slot is allocated to a PU for transmitting its packets. Each PU in a network has infinite buffer. The packet transmission time of PUs equals to the time slot. It is also assumed that each PU is an independent Poisson source with an average packet generation rate \( \lambda_{PB} \) packets per time slot.

2.2 Cognitive Radio Network Model

Our CR network model consists of \( N_{CR} \) CR users and a CR base station in the same communication area with the PUs. Slotted Aloha is utilized as random access scheme by the CR users. The operation of a CR user in the network is as follows. Each CR user makes a decision about the slot usage at the beginning of a time slot. If the time slot is used by a PU, then the CR user waits for the availability of subsequent time slots. If the time slot is idle, then the CR user transmits its packet immediately.

In our CR network model, it is assumed that each CR user generates packets according to Poisson process with an average packet generation rate \( \lambda_{CR} \) packets per time slot. In addition, the packet length of CR users is shorter than that of PUs’ due to the spectrum sensing time.

2.3 Spectrum Sensing

Spectrum sensing is one of the most critical parts of the CR networks as it monitors a given part of the spectrum and makes a binary decision according to spectrum usage. There are several approaches using different spectrum sensing techniques and the primary transmitted signal sensing based on energy detection is the most commonly used among them [2].

Energy detection scheme observes the energy in a certain wireless channel and compares the obtained value with a predefined threshold. If the energy level obtained is above the threshold, it is assumed that the spectrum is active, occupied by PUs. In the other case, the spectrum is assumed to be idle, not occupied by the PUs. The latter case is an opportunity for CR users to exploit the channel without causing harmful interference to the PUs [2]. The energy detection scheme is one of the most commonly used sensing technique in CR networks due to its low complexity and no need of prior information about PUs’ signals [1].

In general, spectrum sensing can be considered as the binary hypothesis testing problem with two possible
hypotheses $\mathcal{H}_0$ which represents the absence of PU and $\mathcal{H}_1$ which represents the presence of PU described as follows,

$$X[n] = \begin{cases} W[n], & \mathcal{H}_0, \\ S[n] + W[n], & \mathcal{H}_1, \end{cases} \quad n = 1, 2, \ldots, N \quad (1)$$

where $X[n]$ is a sample of received signal at a CR user, $W[n]$ is the Additive White Gaussian Noise (AWGN) with zero mean and variance $\sigma_w^2$, and $S[n]$ is the received signal assumed to be an identical and independent random process (i.i.d.) with zero mean and variance $\sigma_s^2$. Signal to Noise Ratio (SNR) of the received signal is denoted by $SNR = \frac{\sigma_s^2}{\sigma_w^2}$.

Essentially, the decision about the channel usage is given as follows [1], [6].

$$E = \sum_{n=0}^{N} \mathbb{H}_1 \frac{|X[n]|^2 > \gamma}{\mathbb{H}_0} \quad (2)$$

where $E$ is the decision statistics, $\gamma$ is a predefined decision threshold, $n$ is the sample index, and $N$ is the number of samples.

Using central limit theorem for a large number of samples, the decision statistics can be given as Gaussian distribution as follows [6],

$$E \sim \begin{cases} \mathcal{N}(N\sigma_w^2, 2N\sigma_w^4), & \mathcal{H}_0 \\ \mathcal{N}(N \sigma_s^2 + \sigma_w^2, 2N(\sigma_s^2 + \sigma_w^2)^2), & \mathcal{H}_1 \end{cases} \quad (3)$$

where $\mathcal{N}(a, b)$ is the normal distribution with mean $a$ and variance $b$. Then $P_d$ and $P_{fa}$ can be defined as follows [6],

$$P_d = P(E \geq \gamma | H_1)$$

$$P_{fa} = P(E \geq \gamma | H_0) \quad (4)$$

where $P_d$ is the probability of detecting a PU signal on a given spectrum when it is really present and $P_{fa}$ is the probability that a CR user incorrectly decides that the given spectrum is occupied by PU when it really is not. Then, $P_d$ and $P_{fa}$ can be calculated as in (5) [2], [6],

$$P_d = Q \left( \frac{\gamma - N(\sigma_s^2 + \sigma_w^2)}{\sqrt{2N(\sigma_s^2 + \sigma_w^2)^2}} \right)$$

$$P_{fa} = Q \left( \frac{\gamma - N\sigma_w^2}{\sqrt{2N\sigma_w^4}} \right) \quad (5)$$

where $Q(\cdot)$ is the generalized Marcum Q-function [6], [7].

So, the number of samples required to meet the desired $P_d$ and $P_{fa}$ parameters under a certain SNR value is written by,

$$N = 2SNR^{-2}[Q^{-1}(P_{fa}) - (1 + SNR)Q^{-1}(P_d)]^2 \quad (6)$$

Consequently, the sensing time, $\tau$, is computed by,

$$\tau = \frac{N}{W} \quad (7)$$

where $W$ is the channel bandwidth [6], [8].

### 2.4 Simulation Model of the Proposed CR Network

We have used OPNET Modeler simulation software to develop, model, and simulate the proposed network scenarios. In our simulation model, there are 10 primary and 10 CR users uniformly distributed in the communication area. Free space channel propagation model is used for predicting the received packet. The other simulation parameters used are given in Table 1.

#### Table 1. Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDMA time slot length</td>
<td>100 ms</td>
</tr>
<tr>
<td>Number of Primary users</td>
<td>10</td>
</tr>
<tr>
<td>Number of CR users</td>
<td>10</td>
</tr>
<tr>
<td>Frequency of the Primary and CR users</td>
<td>4 GHz</td>
</tr>
<tr>
<td>Bandwidth of the Primary and CR users</td>
<td>6 MHz</td>
</tr>
<tr>
<td>Modulation scheme</td>
<td>QPSK</td>
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<tr>
<td>Transmitter power for CR users</td>
<td>50.10^{-2} W</td>
</tr>
<tr>
<td>Probability of detection</td>
<td>0.9</td>
</tr>
<tr>
<td>Probability of false alarm</td>
<td>0.1</td>
</tr>
</tbody>
</table>

### 3. PERFORMANCE EVALUATION

#### 3.1 Throughput Performance of Primary Network

The throughput of primary TDMA network is defined as the average number of packets successfully received by primary base station during a time slot. The offered load of the primary network can be defined as the number of packets presented to the network in a time slot. Since TDMA is a contention-free MAC scheme, there are no collisions among TDMA packets offered to the network. Therefore, when offered load is less than 1, the throughput is equal to the load and when offered load is equal or greater than 1, the throughput is equal to 1. The throughput equation of primary network can be expressed by [8],

$$S_{PR} = \begin{cases} G_{PR}, & G_{PR} < 1 \\ 1, & G_{PR} \geq 1 \end{cases} \quad (8)$$

where $S_{PR}$ and $G_{PR}$ are the primary network throughput and primary network offered load, respectively.

#### 3.2 Throughput Performance of Cognitive Radio Network

For CR users, throughput is the performance metric adopted in this paper. Since CR users utilize slotted Aloha as
a random access scheme, the throughput of CR network can be defined as the number of packets successfully received by the CR base station in a time slot [9]. Therefore, CR users’ throughput can be written as in (9).

\[ S_{CR} = P_{idle} \left( \frac{N_{CR}}{1} \right) P_t (1 - P_t)^{N_{CR} - 1} \] (9)

where \( S_{CR} \) is the CR network throughput, \( P_{idle} \) is the idle probability of PUs, \( N_{CR} \) is the number of CR users in the networking area, and \( P_t \) is the packet transmission probability of a CR user in a time slot. We assume that \( G_{CR} \) is the total offered load presented to the CR network. So, a CR user’s offered load can be calculated as follows,

\[ \lambda_{CR} = \frac{G_{CR}}{N_{CR}} \] (10)

where \( \lambda_{CR} \) is an offered load of a CR user, namely an average packet generation rate of a CR user in a time slot. Since CR users exploit the spectrum holes that are not used by the PUs, they can send their packets only when the absence of PU is detected correctly. Therefore, we define a new parameter for a CR user’s offered load, i.e., average effective offered load \( \bar{\lambda} \).

\[ \bar{\lambda} = \lambda_{CR} \left( \frac{1 - P_{fa}}{1 - P_{fa}} \right) \] (16)

4. NUMERICAL RESULTS

In Figure 3, the primary network throughput is presented for various offered load conditions. In the network scenario, there are 10 PUs each having infinite FIFO buffer and 10 CR users. The number of time slots in a frame equals to the number of PUs. As primary network load is increased from 0.1 to 1, the throughput also increases in the same rate. However, when the primary network load is 1 or more, the throughput remains 1. As seen from the figure, analytical results are precisely match with the simulation results.

In Figure 4, the CR network throughputs for different values of \( P_{idle} \) are shown. In simulation scenario, the number
of both PUs and CR users is 10. Since $P_{idle}$ determines the idle probability of PUs, the lower the primary network throughput, the higher the CR network throughput. As seen from the figure, when $P_{idle} = 1$, which means that the channel is not used by the PUs and completely in the order of CR users’ exploitation, maximum CR network throughputs are obtained for all offered CR network loads. When $P_{idle}$ decreases, the primary network throughput increases and at the same time the CR network throughput decreases. Our analytical results are validated by the simulation results obtained from OPNET Modeler [10].

**5. CONCLUSION**

In this paper, we have considered a slotted Aloha based CR network and evaluated its throughput performance. PUs and CR users share the time slotted based single communication channel. PUs are authorized to access the channel and utilize TDMA as a MAC technique. CR users employ slotted Aloha as a random access scheme and can access the channel when it is not occupied by the PUs. New expressions for the throughput of CR network and the overall network have been derived to evaluate the channel utilization. Besides, an example network scenario has been developed, modeled and simulated by using the OPNET Modeler simulation software in order to verify the analytical throughput results. This study has also shown that the channel utilization of primary TDMA network can be improved by well exploiting the spectrum holes without interfering with the PUs’ transmissions.

**REFERENCES**


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**Figure 4. Proposed cognitive radio network throughput.**

**Figure 5. Primary and overall network throughputs when $P_{idle}=0.1$.**