An Opportunistic Channel Access Scheme for Interweave Cognitive Radio Systems

Sivasothy Senthuran, Alagan Anpalagan, Hyung Yun Kong, Ashok Karmokar, and Olivia Das

Abstract: **We propose a novel opportunistic access scheme for cognitive radios in an interweave cognitive system, that considers the channel gain as well as the predicted idle channel probability (primary user occupancy: Busy/idle). In contrast to previous work where a cognitive user vacates a channel only when that channel becomes busy, the proposed scheme requires the cognitive user to switch to the channel with the next highest idle probability if the current channel's gain is below a certain threshold. We derive the threshold values that maximize the long term throughput for various primary user transition probabilities and cognitive user's relative movement.**

Index Terms: **Channel switching threshold, cognitive radio, opportunistic access, primary user traffic.**

I. INTRODUCTION

Opportunistic communication over fading channels is a well studied subject where the adaptive radio resource allocation and multiuser selection in transmission often exploit the channel fading characteristics [1]. The limited frequency spectrum and under-utilization of the assigned spectrum triggered the need for opportunistic spectrum sharing [2], [3] among users. The users who own the spectrum get higher access privilege, and the opportunistic users (also known as cognitive users) usually look for opportunistic channel access. In an interweave cognitive radio system, the unoccupied spectrum holes should be shared by cognitive users with minimal collision [4]. That is, an effective sensing scheme should be used to find the vacant channels in order to avoid collision. There are many spectrum sensing algorithms proposed in the literature with different techniques [5].

The objective of a channel access scheme is to maximize the long-term throughput of a cognitive user with minimal interference to the primary users. In [6], multi-channel opportunistic sensing was proposed where a cognitive user senses the channel before the access and the cognitive user is limited to sense only one channel at a time. This problem is treated as partially observable Markov decision process for generally correlated channels and their proposed optimal access scheme is intractable and computationally complex. A simple myopic access scheme was proposed in [7] and [8], and it was designed to maximize the throughput of each slot neglecting the impact on the future potential throughput. Hence, this myopic scheme was modeled as a static optimization problem rather than a sequential decision making process. It was not only simple and robust, but also proved to be optimal under the independent and identically distributed Gilbert-Elliot channel model [9]. It was proposed in [8] that a cognitive user senses the most probable idle channel in each slot, and if primary user's traffic is positively correlated, the cognitive user occupies that channel until it becomes busy, i.e., until the primary user starts to use that channel. In that work, the channel fading characteristic was not considered; hence, even if the cognitive user occupies a weak channel, it will stay with that channel until it becomes busy. There could be other channels with good channel gains that are potentially idle for use by cognitive users. This motivates us to investigate a new channel switching strategy in cognitive radio systems.

In this article, a channel switching scheme based on the primary user channel occupancy statistics as well as the cognitive user's received signal to noise ratio (SNR) is proposed, analyzed and verified for a cognitive radio system. Rather than staying in a channel when the cognitive user's received SNR goes below a threshold, a cognitive radio switches to the channel with the next highest idle probability to improve the throughput. Following the formulation of this channel switching problem, optimal switching thresholds that maximize the long term throughput of the cognitive radios are analytically found for different primary users' traffic characteristics using a Markov chain model. Our contributions in this article can be summarized as follows:

- Analytically evaluating the throughput performance of a cognitive user with channel switching for different traffic characteristics of primary users and the relative motion (Doppler spread) of cognitive users.
- Proposing an opportunistic channel switching algorithm and analytically obtaining the optimal channel switching threshold for an interweave cognitive radio system.

The rest of the article is organized as follows. Section II describes the system model under consideration. Section III analyzes the performance of the proposed interweave access scheme with two primary channels first and then with multiple primary channels. Finally, this article concludes with summary and future work in Section V.

II. SYSTEM MODEL

We assume that there are many primary user channels, and one cognitive user pair tries to access an idle channel. Also, we assume that a cognitive user can sense/access only one channel during a time slot and occupies that channel if it is idle; otherwise, it waits for the next time slot. After each sensing, the cognitive user updates the belief vector (Π^O) of the primary

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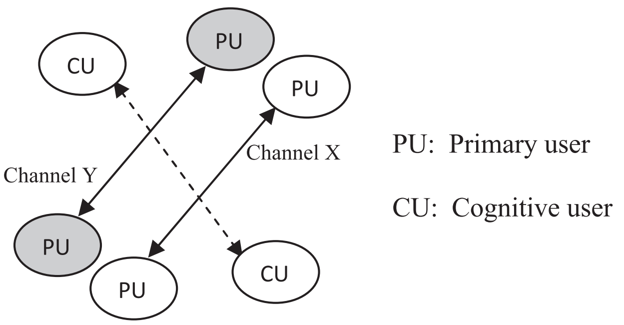

Fig. 1. System model (2 primary user channels and 1 cognitive user pair).

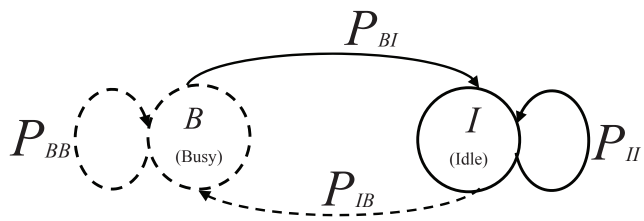

Fig. 2. Markov channel model for occupancy of a primary user.

user occupancy as given in (1). More details about the belief vector and their update are provided later. If the first slot is idle, then it will transmit in that slot and updates the belief vector (Π^H) of the cognitive user's received SNR. During the next time slot, if that current channel's primary user occupancy and cognitive user's SNR prediction are favorable, then the cognitive user will sense the same channel. Otherwise, based on the primary users occupancy prediction (Π^O), the cognitive user will switch the sensing to the most probable idle channel other than the current channel. The primary user's occupancy state prediction and received SNR state prediction models are explained in subsection II-A and subsection II-B, respectively.

In this work, the initial analysis is done for a system that has two identical but independent primary channels and one cognitive user that tries to opportunistically occupy a primary user channel as shown in Fig. 1.

A. Channel Occupancy State

We use a multi-channel cognitive radio system to develop our access scheme. There are N independent, stochastically identical slotted channels, each of which is modeled using a two state Markov chain [9] as in Fig. 2. The busy and idle state of the channel are denoted with *state B* and *state I*, respectively. The transition probability of this Markov chain is denoted by $\{P_{qr}\}_{q,r=B,I}$. P_{II} denotes the probability that a channel becomes idle in the next time slot given that it is idle during the current slot. P_{BI} denotes the probability that a channel becomes idle given that the channel is currently busy; that is, the probability that a primary user leaves the channel during the next time slot after occupying the current slot. The cognitive users can use any learning algorithms to model the primary user statistics [10], [11]. Another approach is to use databases where these statistics can be stored and provided to cognitive users upon request. The idle probability of channel i (Π_i^O) is updated after each slot based on the sensing outcome [6]. That is,

$$\Pi_i^O(t+1) = \begin{cases} P_{II}, & \text{case } \theta_1; \\ P_{BI}, & \text{case } \theta_2; \\ \Pi_i^O(t)P_{II} + (1-\Pi_i^O(t))P_{BI}, & \text{case } \theta_3 \end{cases} \tag{1}$$

where case θ_1 and case θ_2 denote that at time t, the channel i is selected for sensing and it is idle (*state I*) and busy (*state B*), respectively. Case θ_3 denotes that at time t, the channel i is not selected for sensing. The cognitive user communicates opportunistically by using the idle channels of the primary users. The primary user channel state (busy or idle) predication is incorporated with our channel switching strategy. When $P_{II} > P_{BI}$, the probability of an idle channel (*state I*) during the current slot becoming idle in the following slot (P_{II}) is higher than that of a busy channel (*state B*) becoming idle (P_{BI}). Therefore, when a cognitive user senses a channel as idle and when $P_{II} > P_{BI}$, it is better to transmit during that slot and stay in that channel, since there is a higher probability that the channel will become idle during the next time slot. On the other hand, when $P_{BI} > P_{II}$, the probability of an idle channel during the current slot becoming idle in the following slot (P_{II}) is lower than that of a busy channel becoming idle (P_{BI}). Therefore, when a cognitive user senses a channel as idle and when $P_{BI} > P_{II}$, it is better to transmit during that slot and move out of that channel in the next slot, since there is a higher probability that the channel will become busy during the next time slot. The steady state probability if *state I* and *state B* can be written as $P_I = P_{BI}/(P_{BI} + P_{IB})$ and $P_B = 1 - P_I$, respectively.

B. Channel Gain State

The channel gain state modeling is taken from [12]. In a rich multipath propagation environment, the instantaneous received signal amplitude is commonly modeled with the Rayleigh distribution. A slowly varying Rayleigh channel can be modeled as a finite state Markov channel [13] by partitioning the received SNR, which is proportional to the squared of the received signal amplitude, into a finite number of K non-overlapping states. As mentioned in [14], this first order Markov model accurately models the practical fading channel for packet/block level communication when the block length is sufficiently large. Let h be the normalized SNR at the receiver when the transmitter power is P_{power}. The pdf of h is exponentially distributed and can be written as, where h_0 is the average received SNR.

$$p(h) = \frac{1}{h_0} e^{\left(-\frac{h}{h_0}\right)}, \quad \text{for } h \geq 0. \tag{2}$$

Let $H = \{H_l, H_h\}$ denote the state space of the finite state Markov channel. The Rayleigh fading channel is said to be in state H_l and H_h when the received SNR is in the interval $[0, \Gamma)$ and $[\Gamma, \infty)$, respectively. Let P_{H_l} and P_{H_h}denote the steady state probabilities associated with states H_l and H_h, respectively. Hence, $P_{H_l} = \int_0^\Gamma p(h)dh = 1 - \exp(-\Gamma/h_0)$ and $P_{H_h} = \exp(-\Gamma/h_0)$. We assume that the Rayleigh fading channel is slow enough so that the received SNR remains within the certain state for the duration of a block.

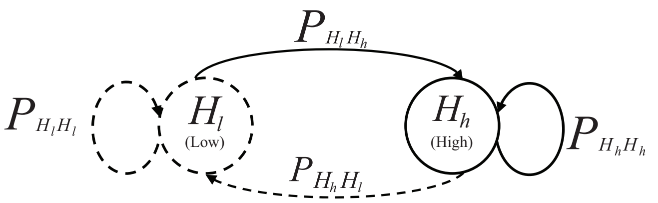

Fig. 3. Two sate Markov channel model for gain state (SNR) of a cognitive user.

The transition probability, $P_{H_lH_h}$ from state H_l to state H_k is approximated by the ratio of the expected number of level crossings at the received SNR (Γ), and the average transmission rate in state H_l. Similarly, the transition probability, $P_{H_hH_l}$ from state H_h to state H_l is approximated by the ratio of the expected number of level crossings at the received SNR Γ and the average transmission rate in state H_h. Let the number of blocks per second of the block-fading channel be R_B, so the average number of blocks/second during which the channel is in state H_l is $R_B^l = P_{H_l}R_B$. Therefore, the crossover transition probabilities can be written as,

$$P_{H_lH_h} \approx \frac{N(\Gamma)}{R_B^l} \tag{3}$$

and similarly,

$$P_{H_hH_l} \approx \frac{N(\Gamma)}{R_B^h} \tag{4}$$

where $N(\Gamma)$ is the expected number of times per second the received SNR passes downward across the corresponding threshold Γ and is given by [12] and [15],

$$N(\Gamma) = \sqrt{\frac{2\pi\Gamma}{h_0}} f_m e^{\left(\frac{-\Gamma}{h_0}\right)}. \tag{5}$$

In this expression, $f_m = v/\lambda$ is the maximum Doppler frequency, where v is the speed of the mobile terminal and λ is the wavelength of the radio wave. The transition probability of staying in the same state can be found as, $P_{H_lH_l} = 1 - P_{H_lH_h}$ and $P_{H_hH_h} = 1 - P_{H_hH_l}$. Average channel capacity (R_{H_h}) in state H_h (assuming unit bandwidth) can be calculated from (2) as follows [16]:

$$R_{H_h} = \int_{\Gamma}^{\infty} \log_2(1+h)\frac{1}{h_0}e^{\frac{-h}{h_0}}dh,$$
$$R_{H_h} = \frac{1}{h_0\ln(2)}\int_{\Gamma}^{\infty} \ln(1+h)e^{\frac{-h}{h_0}}dh$$

by substituting $1 + h = \psi$,

$$\begin{aligned} R_{H_h} &= \frac{1}{h_0\ln(2)}\int_{1+\Gamma}^{\infty}\ln(\psi)e^{\frac{-(\psi-1)}{h_0}}d\psi \\ &= \frac{e^{h_0^{-1}}}{h_0\ln(2)}\int_{1+\Gamma}^{\infty}\ln(\psi)e^{\frac{-\psi}{h_0}}d\psi \\ &= \frac{e^{h_0^{-1}}}{h_0\ln(2)}(-ho)\left(\left[e^{\frac{\psi}{-h_0}}\ln|\psi|\right]_{1+\Gamma}^{\infty} - \int_{1+\Gamma}^{\infty}\frac{e^{\frac{\psi}{-h_0}}}{\psi}d\psi\right) \\ &= \frac{e^{\frac{1}{h_0}}}{\ln(2)}\left[\frac{\ln(1+\Gamma)}{e^{\frac{1+\Gamma}{h_0}}} + E_1\left(\frac{1+\Gamma}{ho}\right)\right] \end{aligned} \tag{6}$$

where $E_1(x) = \int_1^{\infty} t^{-1}e^{-xt}dt,\ x \geq 0$. Similarly, R_{H_l} can be found.

The probability of a channel i being in state H_h (Π_i^H)is updated after each slot based on the sensing outcome. That is,

$$\Pi_i^H(t+1) = \begin{cases} P_{H_hH_h}, & \text{case } \chi_1; \\ P_{H_lH_h}, & \text{case } \chi_2; \\ \Pi_i^H(t)P_{H_hH_h} + (1-\Pi_i^H(t))P_{H_lH_h}, & \text{case } \chi_3 \end{cases} \tag{7}$$

where case χ_1 and case χ_2 denote that at time t, the channel i is selected for sensing and it is sensed as idle. During the transmission it is found that the channel is state H_h and H_l, respectively. Case χ_3 denotes that at time t, the channel i is not selected for sensing or sensed as busy.

C. Channel Access Scheme

As mentioned earlier, our proposed access scheme incorporates prediction of the primary user occupancy state and SNR of the cognitive user. Therefore, even when the current channel has higher probability to become idle during the next time slot, if the cognitive user's predicted SNR is below a threshold (Γ), then the cognitive user switches the sensing to the other channel to potentially improve the throughput in the proposed scheme. The cognitive user switches the channel for sensing due to the following two cases:

i) Case 1: The cognitive user's predicted SNR of the current channel for the next slot is lower than the threshold (Γ) or,
ii) Case 2: The cognitive user senses that the channel is busy (when $P_{II} > P_{BI}$) or idle (when $P_{BI} > P_{II}$) during the current slot.

The proposed channel access scheme is described as follows (See Fig. 4 for corresponding flow chart):

1. Initially the idle probability for all the channels is set to their steady state probability ($P_{BI}/(P_{BI} + P_{IB})$), if not known.
2. Select the most (or second most, from step 4) probable idle channel ($\arg\max \Pi_i^O(t)$) and sense. Update the occupancy belief (1)
3. If it is available, occupy that channel (transmit and update the channel gain belief) during that slot else go to step 2 and wait for the next slot.
4. During the transmission if the corresponding received SNR is above a specified threshold, go to step 2 and sense the most probable idle channel or else sense the second most probable idle channel.

In the proposed system model, the cognitive user can sense only one channel at a time. If that channel is idle, then only it will transmit and get the channel information. Hence, a cognitive user has very limited information about the 'channel gain state' compared to the 'channel occupancy state'. Also, with the proposed algorithm, cognitive user can operate with a simple round robin access scheme. That reduces the processing complexity of the cognitive user. Therefore, it is implemented as: A cognitive user always senses the most probable idle channel. If that channel (that is the sensed most probable idle channel) gives lower SNR, then cognitive user senses the second most probable idle channel.

We consider in the following sections that primary user's occupancy and cognitive user's received SNR are positively corre-

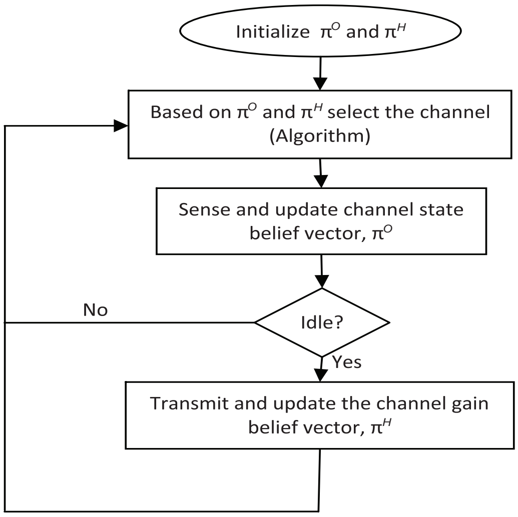

Fig. 4. Flow chart: Channel access scheme in an interweave cognitive system.

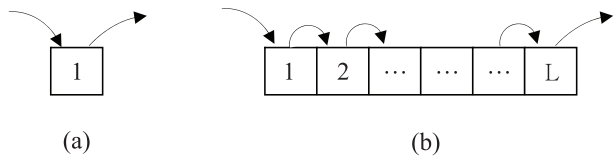

Fig. 5. Sensing cycle: (a) One cognitive user accesses the primary user channels when $P_{II} > P_{BI}$ and (b) cognitive user switches the channel either due to, the current sensed channel is in busy state or the predicted SNR of the current channel for the next slot is lower than the specific threshold.

lated. That is, $P_{II} > P_{BI}$ and $P_{H_hH_h} > P_{H_lH_h}$. In that case, the algorithm will be simplified as follows:

1. Sense the channel, if it is idle (*state I*) transmit during that slot and go to step 2 else switch[1] the channel and wait for the next slot to sense again (step 1).
2. During the transmission if the received SNR is in *state* H_h, stay in that channel and go to step 1 else switch the channel and go to step 1.

We assume that the cognitive user stays in a channel continuously for L (≥ 1) slots. The cognitive user's stay in a channel is modeled as in Fig. 5.

III. ANALYSIS FOR TWO-CHANNEL SYSTEM

In this section, we analyze a cognitive radio system with two primary channels. As we mentioned in subsection II-C, if the predicted SNR is low or the predicted occupancy state is busy, then cognitive user will switch the channel. We combine occupancy state transition (shown in Fig. 2) channel gain transition (shown in Fig. 3) into a four state model in this article and assume these notations $P_{IB} = \alpha$, $P_{BI} = \beta$, $P_{H_hH_l} = \gamma$, and $P_{H_lH_h} = \delta$. The combined transition matrix can be defined using four states IH_h, IH_l, BH_h, and BH_l and denoted by ξ_1, ξ_2, ξ_3, and ξ_4, respectively. The combined transition matrix T_C can be defined as (8),

[1] Round-robin scheme based on a circular ordering is proved to be optimal [8].

Table 1. State classification for analysis purpose.

State	State of the last slot of the previous channel	State of the last slot of the current channel
S_1	ξ_2	ξ_2
S_2	ξ_2	ξ_4
S_3	ξ_2	ξ_3
S_4	ξ_4	ξ_2
S_5	ξ_4	ξ_4
S_6	ξ_4	ξ_3
S_7	ξ_3	ξ_2
S_8	ξ_3	ξ_4
S_9	ξ_3	ξ_3

A cognitive user may leave a channel if, either the occupancy state of the channel is busy (ξ_3) or the predicted SNR during the next slot is low (ξ_2) or both (ξ_4). If the channel is in state ξ_1, cognitive user may stay in that channel. For the analysis purpose, we model the problem into nine different states based on the last state of the current channel and previous channel as in Table 1. Based on the state classification, the state transitions possibilities can be derived as in (9).

$$T = \begin{array}{c} \\ S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \\ S_7 \\ S_8 \\ S_9 \end{array} \begin{array}{c} \begin{array}{ccccccccc} S_1 & S_2 & S_3 & S_4 & S_5 & S_6 & S_7 & S_8 & S_9 \end{array} \\ \begin{pmatrix} * & * & * & - & - & - & - & - & - \\ - & - & - & * & * & * & - & - & - \\ - & - & - & - & - & - & * & * & * \\ * & * & * & - & - & - & - & - & - \\ - & - & - & * & * & * & - & - & - \\ - & - & - & - & - & - & * & * & * \\ * & * & * & - & - & - & - & - & - \\ - & - & - & * & * & * & - & - & - \\ - & - & - & - & - & - & * & * & * \end{pmatrix} \end{array}. \tag{9}$$

We do the analysis based on the above nine states. Each of these nine states can be divided into more than one state depending on the number of slots that the cognitive user stays in a channel continuously. S_K^L denotes that cognitive users stay for L slots ($L = 1, 2, 3, \cdots$) continuously in a channel in state S_K ($K = 1, 2, 3, \cdots, 9$). Fig. 6 shows the channel switching between two channels and its state transitions. For example, consider the following scenario. At time $t = 3$, a cognitive user switches the channel from channel B to channel A, as channel B was in state ξ_3. It again switches back to channel B as it finds the state of the channel A as ξ_4. We consider this one slot stay (at $t = 4$) of the cognitive user in channel A. The state of the last slot of the current channel (channel A, $t = 4$) is ξ_4 and previous channel (channel B, $t = 3$) is ξ_3, from Table 1. Then, we can decide the state of that stay as S_8. Further, as the cognitive user stayed for only one slot, that stay is denoted by S_8^1. Similarly, if we consider the three slots stay in channel B ($t = 10$ to $t = 12$), cognitive user is leaving the channel B during the current visit at $t = 12$ as it is in state ξ_2 and cognitive user left previous channel (channel A, $t = 9$) as it was in state ξ_3, then that stay is denoted by S_7^3.

$T_{S_{K_1}^n S_{K_2}^m}$ denotes the transition probability of a cognitive user that stays in state S_{K_1} for n slots continuously and then moves

$$T_C = \begin{array}{c} \\ \xi_1 \rightarrow \\ \xi_2 \rightarrow \\ \xi_3 \rightarrow \\ \xi_4 \rightarrow \end{array} \begin{array}{c} \begin{array}{cccc} \xi_1(IH_h) & \xi_2(IH_l) & \xi_3(BH_h) & \xi_4(BH_l) \end{array} \\ \begin{pmatrix} (1-\alpha)(1-\gamma) & (1-\alpha)\gamma & \alpha(1-\gamma) & \alpha\gamma \\ (1-\alpha)\delta & (1-\alpha)(1-\delta) & \alpha\delta & \alpha(1-\delta) \\ \beta(1-\gamma) & \beta\gamma & (1-\beta)(1-\gamma) & (1-\beta)\gamma \\ \beta\delta & \beta(1-\delta) & (1-\beta)\delta & (1-\beta)(1-\delta) \end{pmatrix} \end{array}. \tag{8}$$

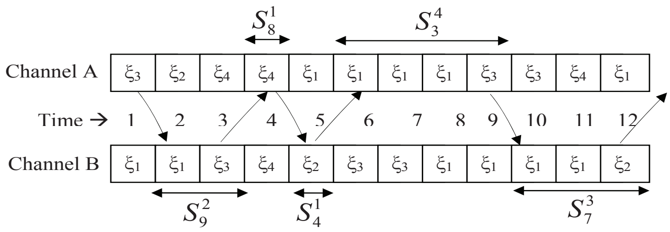

Fig. 6. One cognitive user accesses two primary user channels.

to state S_{K_2} and stays for m slots before leaving that channel. In Fig. 6, cognitive user moves from channel A to channel B at $t = 4$ with transition probability $T_{S_8^1 S_4^1}$. As the previous channel's (channel A, $t = 4$) state is S_8^1, we can say that the state of the last slot during the last visit of the channel B should be ξ_3 ($t = 3$) from Table 1. Similarly, as the current state is S_4^1, we can say that cognitive user leaves the channel after staying for one slot and the state of that channel is ξ_2 (channel B, $t = 5$) from Table 1. As the cognitive user stayed only one slot in the channel A (S_8^1) during the last channel switch, the transition probability can be written as $T^{(2)}_{\xi_3\xi_2}$. That is, $T_{\xi_x\xi_y}$ ($x, y \in 1,2,3,4$) denotes the transition probability from state ξ_x to ξ_y and $T^{(L)}_{\xi_x\xi_y}$ denotes the transition probability from state ξ_x to state ξ_y after L slots ($L = 1, 2, \cdots$) and these transition probabilities can be found from (8). At $t = 5$, the cognitive user switches from state S_4^1 to S_3^4. That implies, the cognitive user left the channel A in the previous visit when the last slot was ξ_4 and stayed one slot in channel B, then switched back to channel A and stays for four slots and leave the channel as it is in state ξ_3. We split the transition probability calculation into three parts as $T_{t=4\rightarrow t=6} = T^{(2)}_{\xi_4\xi_1}$, $T_{t=6\rightarrow t=8} = (T_{\xi_1\xi_1})^2$, and $T_{t=8\rightarrow t=9} = T_{\xi_1\xi_3}$. Hence, the transition probability can be written as $T_{S_4^1 S_3^4} = T^{(2)}_{\xi_4\xi_1}(T_{\xi_1\xi_1})^2 T_{\xi_1\xi_3}$.

Similarly, we can find the other transition probabilities that are listed below.

$$\begin{aligned}
T_{S_1^n S_1^1} &= T_{S_2^n S_4^1} = T_{S_3^n S_7^1} = T^{(n+1)}_{\xi_2\xi_2},\\
T_{S_1^n S_2^1} &= T_{S_2^n S_5^1} = T_{S_3^n S_8^1} = T^{(n+1)}_{\xi_2\xi_4},\\
T_{S_1^n S_3^1} &= T_{S_2^n S_6^1} = T_{S_3^n S_9^1} = T^{(n+1)}_{\xi_2\xi_3},\\
T_{S_1^n S_1^m} &= T_{S_2^n S_4^m} = T_{S_3^n S_7^m} = T^{(n+1)}_{\xi_2\xi_1}(T_{\xi_1\xi_1})^{m-2}T_{\xi_1\xi_2},\\
T_{S_1^n S_2^m} &= T_{S_2^n S_5^m} = T_{S_3^n S_8^m} = T^{(n+1)}_{\xi_2\xi_1}(T_{\xi_1\xi_1})^{m-2}T_{\xi_1\xi_4},\\
T_{S_1^n S_3^m} &= T_{S_2^n S_6^m} = T_{S_3^n S_9^m} = T^{(n+1)}_{\xi_2\xi_1}(T_{\xi_1\xi_1})^{m-2}T_{\xi_1\xi_3},\\
T_{S_4^n S_1^1} &= T_{S_5^n S_4^1} = T_{S_6^n S_7^1} = T^{(n+1)}_{\xi_3\xi_2},\\
T_{S_4^n S_2^1} &= T_{S_5^n S_5^1} = T_{S_6^n S_8^1} = T^{(n+1)}_{\xi_3\xi_4},\\
T_{S_4^n S_3^1} &= T_{S_5^n S_6^1} = T_{S_6^n S_9^1} = T^{(n+1)}_{\xi_3\xi_3},\\
T_{S_4^n S_1^m} &= T_{S_5^n S_4^m} = T_{S_6^n S_7^m} = T^{(n+1)}_{\xi_3\xi_1}(T_{\xi_1\xi_1})^{m-2}T_{\xi_1\xi_2},\\
T_{S_4^n S_2^m} &= T_{S_5^n S_5^m} = T_{S_6^n S_8^m} = T^{(n+1)}_{\xi_3\xi_1}(T_{\xi_1\xi_1})^{m-2}T_{\xi_1\xi_4},\\
T_{S_4^n S_3^m} &= T_{S_5^n S_6^m} = T_{S_6^n S_9^m} = T^{(n+1)}_{\xi_3\xi_1}(T_{\xi_1\xi_1})^{m-2}T_{\xi_1\xi_3},\\
T_{S_7^n S_1^1} &= T_{S_8^n S_4^1} = T_{S_9^n S_7^1} = T^{(n+1)}_{\xi_4\xi_2},\\
T_{S_7^n S_2^1} &= T_{S_8^n S_5^1} = T_{S_9^n S_8^1} = T^{(n+1)}_{\xi_4\xi_4},\\
T_{S_7^n S_3^1} &= T_{S_8^n S_6^1} = T_{S_9^n S_9^1} = T^{(n+1)}_{\xi_4\xi_3},\\
T_{S_7^n S_1^m} &= T_{S_8^n S_4^m} = T_{S_9^n S_7^m} = T^{(n+1)}_{\xi_4\xi_1}(T_{\xi_1\xi_1})^{m-2}T_{\xi_1\xi_2},\\
T_{S_7^n S_2^m} &= T_{S_8^n S_5^m} = T_{S_9^n S_8^m} = T^{(n+1)}_{\xi_4\xi_1}(T_{\xi_1\xi_1})^{m-2}T_{\xi_1\xi_4},\\
T_{S_7^n S_3^m} &= T_{S_8^n S_6^m} = T_{S_9^n S_9^m} = T^{(n+1)}_{\xi_4\xi_1}(T_{\xi_1\xi_1})^{m-2}T_{\xi_1\xi_3}.
\end{aligned}$$

A. Steady State Analysis

In this section, we show the steady state analysis and throughput evaluation of the considered system. If we consider the state S_1^2, we can write the steady state equation as,

$$\begin{aligned}
P_{S_1^2} \;=\;& P_{S_1^1}T_{S_1^1 S_1^2} + P_{S_4^1}T_{S_4^1 S_1^2} + P_{S_7^1}T_{S_7^1 S_1^2}\\
+\;& P_{S_1^2}T_{S_1^2 S_1^2} + P_{S_1^3}T_{S_1^3 S_1^2} + P_{S_1^4}T_{S_1^4 S_1^2}\cdots\\
+\;& P_{S_4^2}T_{S_4^2 S_1^2} + P_{S_4^3}T_{S_4^3 S_1^2} + P_{S_4^4}T_{S_4^4 S_1^2}\cdots\\
+\;& P_{S_7^2}T_{S_7^2 S_1^2} + P_{S_7^3}T_{S_7^3 S_1^2} + P_{S_7^4}T_{S_7^4 S_1^2}\cdots.
\end{aligned}$$

From the transition probabilities found in Section III, we can re-write it as follows:

$$\begin{aligned}
P_{S_1^2} \;=\;& P_{S_1^1}T^{(2)}_{\xi_2\xi_1}T_{\xi_1\xi_2} + P_{S_4^1}T^{(2)}_{\xi_3\xi_1}T_{\xi_1\xi_2} + P_{S_7^1}T^{(2)}_{\xi_4\xi_1}T_{\xi_1\xi_2}\\
+\;& P_{S_1^2}T^{(3)}_{\xi_2\xi_1}T_{\xi_1\xi_2} + P_{S_1^3}T^{(4)}_{\xi_2\xi_1}T_{\xi_1\xi_2} + P_{S_1^4}T^{(5)}_{\xi_2\xi_1}T_{\xi_1\xi_2}\cdots\\
+\;& P_{S_4^2}T^{(3)}_{\xi_3\xi_1}T_{\xi_1\xi_2} + P_{S_4^3}T^{(4)}_{\xi_3\xi_1}T_{\xi_1\xi_2}\cdots\\
+\;& P_{S_7^2}T^{(3)}_{\xi_4\xi_1}T_{\xi_1\xi_2} + P_{S_7^3}T^{(4)}_{\xi_4\xi_1}T_{\xi_1\xi_2}\cdots.
\end{aligned} \tag{10}$$

Similarly, if we write the steady state equations for states S_K^i ($i = 2, 3, \cdots$ and $K = 1, 2, \cdots, 9$), we can find the relationship as:

$$P_{S_K^i} = (T_{\xi_1\xi_1})^{i-2}P_{S_K^2} \tag{11}$$

From (10) and (11) we get,

$$\begin{aligned}
P_{S_1^2} \;=\;& P_{S_1^1}T^{(2)}_{\xi_2\xi_1}T_{\xi_1\xi_2} + P_{S_4^1}T^{(2)}_{\xi_3\xi_1}T_{\xi_1\xi_2} + P_{S_7^1}T^{(2)}_{\xi_4\xi_1}T_{\xi_1\xi_2}\\
+\;& P_{S_1^2}(T^{(3)}_{\xi_2\xi_1} + (T_{\xi_1\xi_1})T^{(4)}_{\xi_2\xi_1} + (T_{\xi_1\xi_1})^2T^{(5)}_{\xi_2\xi_1}\cdots)T_{\xi_1\xi_2}\\
+\;& P_{S_4^2}(T^{(3)}_{\xi_3\xi_1} + (T_{\xi_1\xi_1})T^{(4)}_{\xi_3\xi_1}\cdots)T_{\xi_1\xi_2}\\
+\;& P_{S_7^2}(T^{(3)}_{\xi_4\xi_1} + (T_{\xi_1\xi_1})T^{(4)}_{\xi_4\xi_1}\cdots)T_{\xi_1\xi_2}.
\end{aligned}$$

$$P_{S_1^2} = P_{S_1^1} T^{(2)}_{\xi_2\xi_1} T_{\xi_1\xi_2} + P_{S_4^1} T^{(2)}_{\xi_3\xi_1} T_{\xi_1\xi_2} + P_{S_7^1} T^{(2)}_{\xi_4\xi_1} T_{\xi_1\xi_2} + \left(P_{S_1^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_2\xi_1} + P_{S_4^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_3\xi_1} + P_{S_7^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_4\xi_1} \right) T_{\xi_1\xi_2}. \tag{12}$$

This can be simplified as in (12). Similarly, for other states with two slot stay and one slot stay, we can write the steady state equations as in Appendix A.

Further, we can write

$$\sum_{K=1}^{9} \sum_{i=1}^{\infty} P_{S_K^i} = 1,$$
$$\sum_{K=1}^{9} \left(P_{S_K^1} + \sum_{i=2}^{\infty} P_{S_K^i} \right) = 1. \tag{13}$$

From (11) and (13),

$$\sum_{K=1}^{9} \left(P_{S_K^1} + P_{S_K^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} \right) = 1,$$
$$\sum_{K=1}^{9} \left(P_{S_K^1} + \frac{P_{S_K^2}}{(T_{\xi_1\xi_1})^{i-2}} \right) = 1. \tag{14}$$

The series sum in (12)–(22) can be calculated using eigenvalue decomposition. The square matrix T_C defined in (8) can be written as,

$$T_C = VDV^{-1} \tag{15}$$

where D and V denote a diagonal matrix of eigenvalues and a full matrix whose columns are the corresponding eigenvectors of matrix T_C, respectively. The diagonal elements of the matrix D can be denoted by λ_1, λ_2, λ_3, and λ_4. Using the above properties, $T^{(i+1)}_{\xi_1\xi_3}$, for any positive integer i, can be calculated as $T^{(i+1)}_{\xi_1\xi_3} = (VD^{i+1}V^{-1})_{(1,3)}$. The infinite series sum can be found as shown below,

$$\sum_{i=2}^{\infty} (T_{\xi_1\xi_3})^{i-2} T^{(i+1)}_{\xi_1\xi_1} = (V\bar{D}V^{-1})_{(1,3)}$$

where

$$\bar{D} = \begin{pmatrix} \frac{(\lambda_1)^3}{1-T_{\xi_1\xi_1}\lambda_1} & 0 & 0 & 0 \\ 0 & \frac{(\lambda_2)^3}{1-T_{\xi_1\xi_1}\lambda_2} & 0 & 0 \\ 0 & 0 & \frac{(\lambda_3)^3}{1-T_{\xi_1\xi_1}\lambda_3} & 0 \\ 0 & 0 & 0 & \frac{(\lambda_4)^3}{1-T_{\xi_1\xi_1}\lambda_4} \end{pmatrix}.$$

Similarly, we can find the other infinite series sum. Solving the linear equations (12)–(22) and (14), we can find the steady state probabilities of all the states. The average continuous stay in a channel can be found as follows

$$\begin{aligned} \bar{L} &= \sum_{K=1}^{9} \left(P_{S_K^1} + \sum_{i=2}^{\infty} i \times P_{S_K^i} \right) \\ &= \sum_{K=1}^{9} \left(P_{S_K^1} + P_{S_K^2} \sum_{i=2}^{\infty} i \times (T_{\xi_1\xi_1})^{i-2} \right) \\ &= \sum_{K=1}^{9} \left(P_{S_K^1} + P_{S_K^2} \frac{2 - T_{\xi_1\xi_1}}{(1 - T_{\xi_1\xi_1})^2} \right). \end{aligned} \tag{16}$$

The cognitive user switches a channel in the states S_1, S_4 and S_7 only because of the predicted SNR is low even though the channel is idle (ξ_2). Therefore, a cognitive user may transmit during that last slot and leave that channel. On the other hand, cognitive user leaves the other states as the primary channel is busy. Hence, cognitive user will not transmit during the last of those six states. The last slot throughput can be written as

$$\begin{aligned} C_1 &= R_{H_l} \sum_{i=1}^{\infty} (P_{S_1^i} + P_{S_4^i} + P_{S_7^i}) \\ &= R_{H_l} \left(P_{S_1^1} + P_{S_4^1} + P_{S_7^1} + \frac{P_{S_1^2} + P_{S_4^2} + P_{S_7^2}}{1 - T_{\xi_1\xi_1}} \right) \end{aligned}$$

and during the other slots, gain state of the channel would be higher. Hence, throughput (for $L > 2$) can be written as,

$$\begin{aligned} C_2 &= R_{H_h} \sum_{K=1}^{9} \sum_{i=2}^{\infty} ((i-1) P_{S_K^i}) \\ &= R_{H_h} \sum_{K=1}^{9} \left(\frac{P_{S_K^2}}{(1 - T_{\xi_1\xi_1})^2} \right). \end{aligned}$$

The average throughput can be written as

$$\bar{C} = \frac{C_1 + C_2}{\bar{L}}. \tag{17}$$

B. Analytical Results

In this section we discuss the results of the cognitive radio system with two primary channels. In Fig. 7, we verify the accuracy of the analytical results using Monte Carlo simulations for a positively correlated channel with $P_{BI} = 0.4$, $P_{IB} = 0.1$, and Doppler spread $f_m = 150$ Hz. The horizontal solid line shows the throughput of a secondary user when there is no channel gain based switching (conventional scheme). That is, secondary user levees the channel only when the primary channel becomes busy.

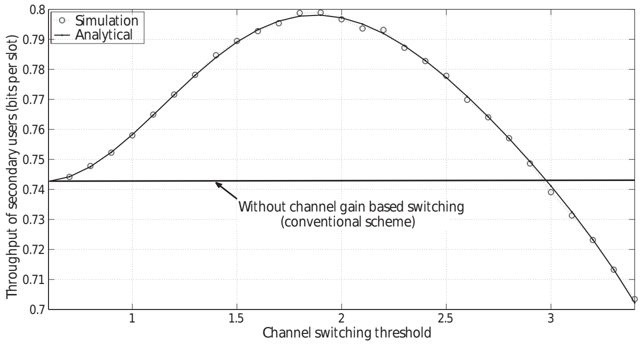

Fig. 7. Throughput performance for different channel switching threshold ($P_{BI} = 0.4, P_{IB} = 0.1, f_m = 150$ Hz).

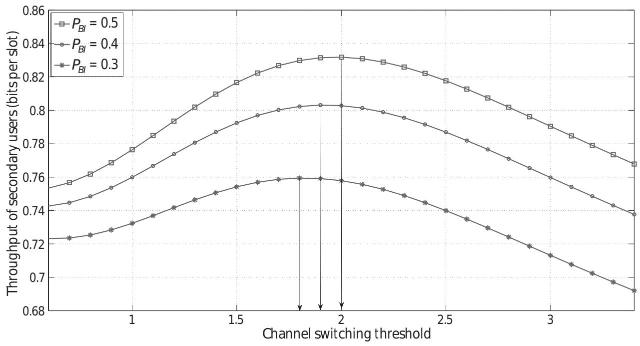

Fig. 8. Throughput performance for different channel switching threshold ($P_{IB} = 0.1, f_m = 20$ Hz).

Fig. 8 shows the optimal channel switching thresholds for different P_{BI} for a system with Doppler spread $f_m = 20$ Hz and $P_{IB} = 0.1$. When $P_{BI} = 0.3$, if the predicted SNR is below 1.8, it is better to switch the channel and if it is above then better to stay in that channel until it becomes busy. Similarly for different scenarios, we can find the optimal channel switching strategy.

IV. STEADY STATE ANALYSIS WITH MULTI CHANNELS

We now analyze the performance of a cognitive radio system with multiple primary user channels assuming that there are more than $N(> 2)$ primary channels and a cognitive user can access any channel if it is not occupied by the primary user. As we consider the round robin access, if there are enough channels, the state of the first slot of a channel that the cognitive user accessed long time back will have *steady state* probabilities after few time slots. That assumption made the analysis simpler compared to the two-channel case.

As we consider channel occupancy state (B or I) and SNR state (H_l or H_h), the first slot can be in any combination. If the sensed channel is busy (B), or idle (I) with lower SNR (H_l), the cognitive user will leave that channel. In that case, it is considered as cognitive user stayed only one slot ($L = 1$) in that channel (Fig. 5(a)). If that channel is in busy state, without transmission, cognitive user will switch the channel. If that channel is idle but with lower SNR, with probability $P_I P_{H_l}/(P_B + P_I P_{H_l})$, it will transmit during that slot and leave that channel right after. Probability of success in accessing the first slot (fs) of a primary channel can be written, using the steady state probabilities, as $P_{fs} = P_I P_{H_h}$. Therefore, if cognitive user stays only one slot, the reward can be written as

$$R_{L=1} = (1 - P_{fs}) \frac{P_I P_{H_l}}{P_B + P_I P_{H_l}} R_{H_l} \tag{18}$$

where R_{H_l} denotes the reward (throughput) during the low SNR (state H_l) transmission.

When sensing, if the channel is idle (I) and having higher gain (H_h), then cognitive user will transmit and will stay in that channel to sense during the next time slot. Probability of staying in the same channel during the next slot (ns) can be written as $P_{ns} = P_{II} P_{H_h H_h}$ and probability of leaving a currently occupied channel can be written as $(1 - P_{ns})$.

When the cognitive user stays L (> 1) number of slots, it may leave the channel when the channel occupancy state becomes busy or the SNR state becomes H_l (Fig. 5(b)). If a cognitive user leaves the channel due to busy state, it will not transmit in the last slot. Hence, the reward during the last slot can be written, considering one slot before the last slot was in state I with H_h, as

$$R_{LastSlot} = \frac{P_{II} P_{H_h H_l}}{P_{IB} + P_{II} P_{H_h H_l}} R_{H_l}. \tag{19}$$

Therefore, if a cognitive user stays in a channel for L slots, the total reward can be written as in (20).

$$\begin{aligned} R = &(1 - P_{fs}) \frac{P_I P_{H_l}}{P_B + P_I P_{H_l}} R_{H_l} \\ &+ P_{fs} \left(\frac{1}{1 - P_{ns}} R_{H_h} + \frac{P_{II} P_{H_h H_l}}{P_{IB} + P_{II} P_{H_h H_l}} R_{H_l} \right). \end{aligned} \tag{20}$$

Average continuous stay in a channel can be found as

$$\begin{aligned} \widetilde{L} &= (1 - P_{fs}) + \sum_{j=2}^{\infty} \left(j P_{fs} (P_{ns})^{(j-2)} (1 - P_{ns}) \right) \\ &= (1 - P_{fs}) + P_{fs} \frac{2 - P_s}{1 - P_s}. \end{aligned}$$

Hence, the average throughput can be derived as

$$\bar{R} = \frac{R}{\widetilde{L}}. \tag{21}$$

A. Analytical Results

In this section, we present and discuss the throughput performance of the proposed access scheme for a cognitive radio system with multiple primary channels. The proposed channel switching scheme provides the optimal channel switching threshold for a given traffic characteristics of primary users and the relative motion (Doppler spread) of cognitive user given that cognitive user can sense only one channel.

The cognitive user's throughput performance for different channel switching thresholds is shown for different primary

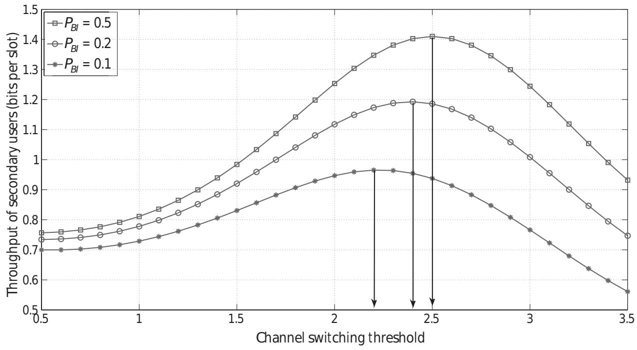

Fig. 9. Throughput performance for different channel switching threshold ($P_{IB} = 0.1, f_m = 20$ Hz).

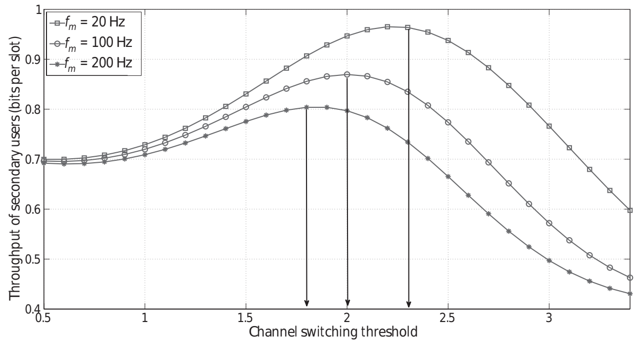

Fig. 11. Throughput performance for different channel switching threshold ($P_{IB} = 0.1, P_{BI} = 0.1$).

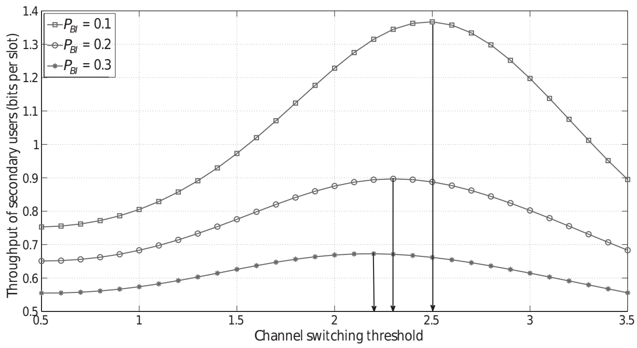

Fig. 10. Throughput performance for different channel switching threshold ($P_{BI} = 0.4, f_m = 20$ Hz).

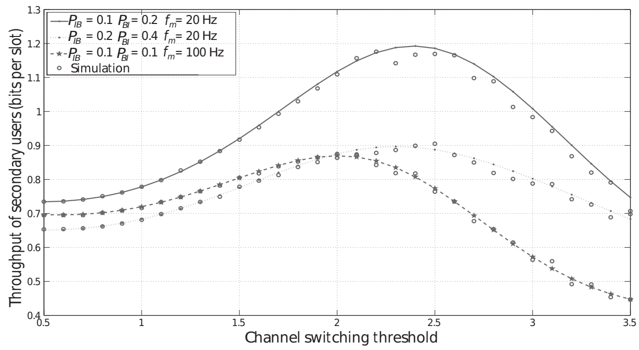

Fig. 12. Throughput performance for different channel switching threshold.

user occupancy statistics. For Doppler spread $f_m = 20$ Hz, $P_{BI} = 0.1$, and $P_{IB} = 0.1$, the optimal channel switching threshold, $\Gamma = 2.2$, can be found in Fig. 9. That is, when the received SNR is below 2.2, it is better to switch the channel for long term throughput benefit even the current channel is in idle state. Also we can find that $\Gamma = 2.5$ when $P_{BI} = 0.5$. In a positively correlated primary user traffic, the cognitive user leaves a channel when it finds that channel is in state B. When a cognitive user switches the channel, it expects that the channels were in busy state during its previous visit may be in idle state after few slots. If the channel's P_{BB} is higher, there is lower probability that the switched channel will be in idle state compared to the channel with lower P_{BB}. Therefore, it is better to stay in the same channel if it is idle even the predicted SNR is not good. We can observe in Fig. 9 that when P_{BI} decreases (or P_{BB} increases) the channel switching threshold also decreases. That is, the access scheme encourages the users to stay in the same channel if it is idle even the predicted SNR is not good for the long term throughput advantage when P_{BB} increases ($P_{BB} = 1 - P_{BI}$).

Further, when P_{II} increases (P_{IB} decreases), the channel switching threshold also increases. We can observe in Fig. 10 that Γ increases from 2.2 to 2.5 when P_{IB} decreases from 0.3 to 0.1 for $P_{BI} = 0.4$ and $f_m = 20$ Hz.

Fig. 11 shows the throughput performance for different Doppler spreads. When the Doppler spread increases, the SNR prediction is not reliable and hence, the channel switching threshold decreases. That is, in a dynamic environment the channel switching based on the channel gain is discouraged for the long term throughput benefit of the cognitive user. We can observe that in Fig. 11 for $P_{BI} = P_{IB} = 0.1$, when Doppler spread f_m increases from 20 Hz to 200 Hz, the optimal channel switching threshold increases from 1.8 to 2.3. Finally the theoretical analysis is verified with simulation in Fig. 12. Three scenarios are selected from Figs. 9–11 (one from each figure) to verify the analysis. Simulation is done for 10^5 time slots in a system with 30 primary channels. When the number of simulation time slots and primary channels increase, simulation results closely match the analysis.

V. CONCLUSION AND FUTURE WORK

In this paper, we analyzed a channel access scheme for a cognitive user that operates in an interweave system, based on the traffic characteristics of the primary system and Doppler spread of the cognitive user. In a positively correlated primary user traffic, the cognitive user switches the channel either when the sensed primary channel is busy or predicted SNR is below a specific threshold. It is found that, when the primary user traffic is highly correlated (higher P_{BB} and P_{II}) or cognitive user is more dynamic (higher f_m), it is not beneficial to switch the channel frequently in order to gain long term throughput advantage. For given statistics about primary user traffic, an optimal channel switching threshold can be found from the analysis that maximizes the long term throughput of a cognitive user.

APPENDIX

For two slot stay, we can write the steady state equations as follows

$$
\begin{aligned}
P_{S_1^2} =\ & P_{S_1^1} T^{(2)}_{\xi_2\xi_1} T_{\xi_1\xi_2} + P_{S_4^1} T^{(2)}_{\xi_3\xi_1} T_{\xi_1\xi_2} + P_{S_7^1} T^{(2)}_{\xi_4\xi_1} T_{\xi_1\xi_2} \\
& + \left(P_{S_1^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_2\xi_1} + P_{S_4^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_3\xi_1} \right. \\
& \left. + P_{S_7^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_4\xi_1} \right) T_{\xi_1\xi_2},
\end{aligned}
$$

$$
\begin{aligned}
P_{S_2^2} =\ & P_{S_1^1} T^{(2)}_{\xi_2\xi_1} T_{\xi_1\xi_4} + P_{S_4^1} T^{(2)}_{\xi_3\xi_1} T_{\xi_1\xi_4} + P_{S_7^1} T^{(2)}_{\xi_4\xi_1} T_{\xi_1\xi_4} \\
& + \left(P_{S_1^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_2\xi_1} + P_{S_4^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_3\xi_1} \right. \\
& \left. + P_{S_7^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_4\xi_1} \right) T_{\xi_1\xi_4},
\end{aligned}
$$

$$
\begin{aligned}
P_{S_3^2} =\ & P_{S_1^1} T^{(2)}_{\xi_2\xi_1} T_{\xi_1\xi_3} + P_{S_4^1} T^{(2)}_{\xi_3\xi_1} T_{\xi_1\xi_3} + P_{S_7^1} T^{(2)}_{\xi_4\xi_3} T_{\xi_1\xi_3} \\
& + \left(P_{S_1^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_2\xi_1} + P_{S_4^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_3\xi_1} \right. \\
& \left. + P_{S_7^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_4\xi_1} \right) T_{\xi_1\xi_3},
\end{aligned}
$$

$$
\begin{aligned}
P_{S_4^2} =\ & P_{S_3^1} T^{(2)}_{\xi_2\xi_1} T_{\xi_1\xi_2} + P_{S_6^1} T^{(2)}_{\xi_3\xi_1} T_{\xi_1\xi_2} + P_{S_9^1} T^{(2)}_{\xi_4\xi_1} T_{\xi_1\xi_2} \\
& + \left(P_{S_3^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_2\xi_1} + P_{S_6^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_3\xi_1} \right. \\
& \left. + P_{S_9^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_4\xi_1} \right) T_{\xi_1\xi_2},
\end{aligned}
$$

$$
\begin{aligned}
P_{S_5^2} =\ & P_{S_3^1} T^{(2)}_{\xi_2\xi_1} T_{\xi_1\xi_4} + P_{S_6^1} T^{(2)}_{\xi_3\xi_1} T_{\xi_1\xi_4} + P_{S_9^1} T^{(2)}_{\xi_4\xi_1} T_{\xi_1\xi_4} \\
& + \left(P_{S_3^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_2\xi_1} + P_{S_6^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_3\xi_1} \right. \\
& \left. + P_{S_9^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_4\xi_1} \right) T_{\xi_1\xi_4},
\end{aligned}
$$

$$
\begin{aligned}
P_{S_6^2} =\ & P_{S_3^1} T^{(2)}_{\xi_2\xi_1} T_{\xi_1\xi_3} + P_{S_6^1} T^{(2)}_{\xi_3\xi_1} T_{\xi_1\xi_3} + P_{S_9^1} T^{(2)}_{\xi_4\xi_3} T_{\xi_1\xi_3} \\
& + \left(P_{S_3^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_2\xi_1} + P_{S_6^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_3\xi_1} \right. \\
& \left. + P_{S_9^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_4\xi_1} \right) T_{\xi_1\xi_3},
\end{aligned}
$$

$$
\begin{aligned}
P_{S_7^2} =\ & P_{S_2^1} T^{(2)}_{\xi_2\xi_1} T_{\xi_1\xi_2} + P_{S_5^1} T^{(2)}_{\xi_3\xi_1} T_{\xi_1\xi_2} + P_{S_8^1} T^{(2)}_{\xi_4\xi_1} T_{\xi_1\xi_2} \\
& + \left(P_{S_2^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_2\xi_1} + P_{S_5^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_3\xi_1} \right. \\
& \left. + P_{S_8^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_4\xi_1} \right) T_{\xi_1\xi_2},
\end{aligned}
$$

$$
\begin{aligned}
P_{S_8^2} =\ & P_{S_2^1} T^{(2)}_{\xi_2\xi_1} T_{\xi_1\xi_4} + P_{S_5^1} T^{(2)}_{\xi_3\xi_1} T_{\xi_1\xi_4} + P_{S_8^1} T^{(2)}_{\xi_4\xi_1} T_{\xi_1\xi_4} \\
& + \left(P_{S_2^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_2\xi_1} + P_{S_5^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_3\xi_1} \right. \\
& \left. + P_{S_8^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_4\xi_1} \right) T_{\xi_1\xi_4},
\end{aligned}
$$

$$
\begin{aligned}
P_{S_9^2} =\ & P_{S_2^1} T^{(2)}_{\xi_2\xi_1} T_{\xi_1\xi_3} + P_{S_5^1} T^{(2)}_{\xi_3\xi_1} T_{\xi_1\xi_3} + P_{S_8^1} T^{(2)}_{\xi_4\xi_3} T_{\xi_1\xi_3} \\
& + \left(P_{S_2^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_2\xi_1} + P_{S_5^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_3\xi_1} \right. \\
& \left. + P_{S_8^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_4\xi_1} \right) T_{\xi_1\xi_3}.
\end{aligned}
$$

For one slot stay, we can write the steady state equations as follows

$$
\begin{aligned}
P_{S_1^1} =\ & P_{S_1^1} T^{(2)}_{\xi_2\xi_2} + P_{S_4^1} T^{(2)}_{\xi_3\xi_2} + P_{S_7^1} T^{(2)}_{\xi_4\xi_2} \\
& + \left(P_{S_1^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_2\xi_2} + P_{S_4^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_3\xi_2} \right. \\
& \left. + P_{S_7^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_4\xi_2} \right),
\end{aligned}
$$

$$
\begin{aligned}
P_{S_2^1} =\ & P_{S_1^1} T^{(2)}_{\xi_2\xi_4} + P_{S_4^1} T^{(2)}_{\xi_3\xi_4} + P_{S_7^1} T^{(2)}_{\xi_4\xi_4} \\
& + \left(P_{S_1^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_2\xi_4} + P_{S_4^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_3\xi_4} \right. \\
& \left. + P_{S_7^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_4\xi_4} \right),
\end{aligned}
$$

$$
\begin{aligned}
P_{S_3^1} =\ & P_{S_1^1} T^{(2)}_{\xi_2\xi_3} + P_{S_4^1} T^{(2)}_{\xi_3\xi_3} + P_{S_7^1} T^{(2)}_{\xi_4\xi_3} \\
& + \left(P_{S_1^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_2\xi_3} + P_{S_4^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_3\xi_3} \right. \\
& \left. + P_{S_7^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_4\xi_3} \right),
\end{aligned}
$$

$$
\begin{aligned}
P_{S_4^1} =\ & P_{S_3^1} T^{(2)}_{\xi_2\xi_2} + P_{S_6^1} T^{(2)}_{\xi_3\xi_2} + P_{S_9^1} T^{(2)}_{\xi_4\xi_2} \\
& + \left(P_{S_3^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_2\xi_2} + P_{S_6^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_3\xi_2} \right. \\
& \left. + P_{S_9^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_4\xi_2} \right),
\end{aligned}
$$

$$
\begin{aligned}
P_{S_5^1} =\ & P_{S_3^1} T^{(2)}_{\xi_2\xi_4} + P_{S_6^1} T^{(2)}_{\xi_3\xi_4} + P_{S_9^1} T^{(2)}_{\xi_4\xi_4} \\
& + \left(P_{S_3^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_2\xi_4} + P_{S_6^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_3\xi_4} \right. \\
& \left. + P_{S_9^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_4\xi_4} \right),
\end{aligned}
$$

$$
\begin{aligned}
P_{S_6^1} =\ & P_{S_3^1} T^{(2)}_{\xi_2\xi_3} + P_{S_6^1} T^{(2)}_{\xi_3\xi_3} + P_{S_9^1} T^{(2)}_{\xi_4\xi_3} \\
& + \left(P_{S_3^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_2\xi_3} + P_{S_6^2} \sum_{i=2}^{\infty} (T_{\xi_1\xi_1})^{i-2} T^{(i+1)}_{\xi_3\xi_3} \right.
\end{aligned}
$$

$$+P_{S_9^2}\sum_{i=2}^{\infty}(T_{\xi_1\xi_1})^{i-2}T_{\xi_4\xi_3}^{(i+1)}\Bigg),$$

$$P_{S_7^1}=P_{S_2^1}T_{\xi_2\xi_2}^{(2)}+P_{S_5^1}T_{\xi_3\xi_2}^{(2)}+P_{S_8^1}T_{\xi_4\xi_2}^{(2)}$$
$$+\Bigg(P_{S_2^2}\sum_{i=2}^{\infty}(T_{\xi_1\xi_1})^{i-2}T_{\xi_2\xi_2}^{(i+1)}+P_{S_5^2}\sum_{i=2}^{\infty}(T_{\xi_1\xi_1})^{i-2}T_{\xi_3\xi_2}^{(i+1)}$$
$$+P_{S_8^2}\sum_{i=2}^{\infty}(T_{\xi_1\xi_1})^{i-2}T_{\xi_4\xi_2}^{(i+1)}\Bigg),$$

$$P_{S_8^1}=P_{S_2^1}T_{\xi_2\xi_4}^{(2)}+P_{S_5^1}T_{\xi_3\xi_4}^{(2)}+P_{S_8^1}T_{\xi_4\xi_4}^{(2)}$$
$$+\Bigg(P_{S_2^2}\sum_{i=2}^{\infty}(T_{\xi_1\xi_1})^{i-2}T_{\xi_2\xi_4}^{(i+1)}+P_{S_5^2}\sum_{i=2}^{\infty}(T_{\xi_1\xi_1})^{i-2}T_{\xi_3\xi_4}^{(i+1)}$$
$$+P_{S_8^2}\sum_{i=2}^{\infty}(T_{\xi_1\xi_1})^{i-2}T_{\xi_4\xi_4}^{(i+1)}\Bigg),$$

$$P_{S_9^1}=P_{S_2^1}T_{\xi_2\xi_3}^{(2)}+P_{S_5^1}T_{\xi_3\xi_3}^{(2)}+P_{S_8^1}T_{\xi_4\xi_3}^{(2)}$$
$$+\Bigg(P_{S_2^2}\sum_{i=2}^{\infty}(T_{\xi_1\xi_1})^{i-2}T_{\xi_2\xi_3}^{(i+1)}+P_{S_5^2}\sum_{i=2}^{\infty}(T_{\xi_1\xi_1})^{i-2}T_{\xi_3\xi_3}^{(i+1)}$$
$$+P_{S_8^2}\sum_{i=2}^{\infty}(T_{\xi_1\xi_1})^{i-2}T_{\xi_4\xi_3}^{(i+1)}\Bigg).$$

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