Exploiting Multichannel Diversity in Cognitive Radio Networks

Tuan Do and Brian L. Mark
Dept. of Electrical and Computer Engineering
George Mason University, MS 1G5
4400 University Drive, Fairfax, VA

***Abstract*—Cognitive radios hold tremendous promise for increasing spectral efficiency in wireless systems. In cognitive radio networks, secondary users equipped with frequency-agile cognitive radios communicate with one another via spectrum that is not being used by the primary, licensed users of the spectrum. We consider a multichannel cognitive radio network scenario in which a secondary transmitter can switch to different channels for opportunistic communications. Multichannel diversity can be achieved by dynamically switching to different channels during transmission. Our numerical results show that even a simple randomized channel switching scheme can significantly reduce the average symbol error probability. We also propose a scheduling algorithm based on maximizing signal-to-noise ratio to further improve the performance of cognitive transmission.**

***Index Terms*—Cognitive radio, multichannel diversity**

I. INTRODUCTION

As wireless devices and applications continue to grow, more and more spectrum resources will be needed. In the current spectrum regulatory framework, spectrum or frequency is allocated to licensed users over a geographic area. Within these constraints, spectrum is considered a scarce resource due to static spectrum allocation. Recent empirical studies of radio spectrum usage have shown that licensed spectrum is typically highly underutilized [1], [2]. To recapture the so-called "spectrum holes," various schemes for allowing unlicensed or secondary users to opportunistically access unused spectrum have been proposed. Opportunistic or dynamic spectrum access is achieved by cognitive radios that are capable of sensing the radio environment for spectrum holes and dynamically tuning to different frequency channels to access them. Such radios are often called *frequency-agile* or *spectrum-agile*.

On a given frequency channel, a spectrum hole can be characterized as spatial or temporal. A *spatial* spectrum hole can be specified in terms of the maximum transmission power that a secondary user can employ without causing harmful interference to primary users that are receiving transmissions from another primary user that is transmitting on the given channel. Spatial spectrum sensing is investigated in [3], wherein the maximum interference-free transmit power (MIFTP) of a given secondary user is estimated based on signal strengths received by a group of secondary nodes. To calculate the MIFTP for a secondary node, estimates of both the location and transmit power of the primary transmitter are estimated collaboratively by a group of secondary nodes. Using these estimates, each secondary node determines its approximate MIFTP, which bounds the size of its spatial spectrum hole.

A *temporal* spectrum hole is a period of time for which the primary transmitter is idle. During such idle periods, a secondary user may opportunistically transmit on the given channel without causing harmful interference. The problem of detecting when the primary is ON or OFF is called *temporal* spectrum sensing. Cooperative temporal sensing has been studied in [4], [5]. The decision on the ON/OFF status of the primary transmitter can be made either at individual secondary nodes or collaboratively by a group of secondary nodes. In [6], a temporal spectrum sensing strategy that exploits multiuser diversity among secondary nodes is proposed.

In an earlier paper [7], a joint spatial-temporal sensing was proposed whereby a secondary node performs spatial sensing to determine its MIFTP when the primary transmitter is ON and uses localization information obtained in the process of spatial sensing to improve the performance of temporal sensing, which estimates the ON/OFF state of the primary transmitter. In [8], a combined joint spatial-temporal sensing and amplify-and-forward cooperative relaying scheme was proposed to improve the performance of cognitive transmission. A decode-and-forward cooperative communication scheme was investigated in [9].

In this paper, we consider a multichannel cognitive radio network in which N primary transmitters (PTs) operate on N different channels with frequencies f_i, $i = 1, \dots, N$. Multichannel cognitive radio networks have been studied in [10]–[13]. In [11], [12], a dynamic programming approach was proposed to search for an optimal sensing order among the channels. In [10], a *channel-aware switching* algorithm was developed to decide *where* and *when* to switch among the candidate channels. Sequential temporal sensing algorithms were developed for OFDM-based hierarchical cognitive radio systems in [13]. In all of the aforementioned works, only pure temporal spectrum sensing was considered.

In this paper, we investigate channel switching in multichannel cognitive radio networks employing joint spatial-temporal sensing. In our scheme, secondary users can switch to a new channel even when the primary user on that channel is ON and continue to transmit using MIFTP. We show that even for a simple randomized channel switching scheme, our scheme outperforms the conventional scheme in which secondary users stay on the same channel during transmission. We also pro-

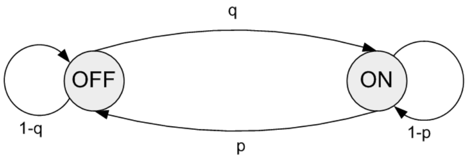

Fig. 1. 2-state Markov chain model for PT ON/OFF process.

pose a “maximized signal-to-noise ratio” scheduling scheme that can further improve the performance of secondary user transmissions.

The remainder of the paper is organized as follows. Section II describes the system model. Section III discusses the randomized channel switching algorithm and its performance. The maximizing SNR scheduling algorithm is proposed in Section IV. Section V presents simulation results. Finally, the paper is concluded in Section VI.

II. SYSTEM MODEL

A. Transmission frames and PT behavior

We assume that the licensed wireless spectrum consists of N non-overlapping channels with frequencies f_i, $i = 1, 2, \ldots, N$. There is one PT on each channel. Secondary users are equipped with a single half-duplex transceiver capable of switching to different channels. Time on the wireless channel is divided into frames consisting of N_s symbols. Each PT alternates between ON and OFF states on a per-frame basis according to the on-off Markov model of Fig. 1. The ON/OFF states of different PTs are statistically independent. The ON and OFF durations of PT i are modeled by geometric random variables with parameters q_i and p_i, respectively (cf. [14]). The steady-state probabilities that PT i is ON and OFF are given by $p_i^{\text{on}} = q_i/(p_i + q_i)$ and $p_i^{\text{off}} = p_i/(p_i + q_i)$, respectively.

B. Channel modeling

When a PT is ON, a secondary transmitter (ST) is limited in the amount of power it can use in order to avoid causing harmful interference to the primary users who receive the transmissions from the PT. The maximum power that can be used by a given secondary node while avoiding harmful interference to primary users is called the *maximum interference-free transmit power* (MIFTP) (cf. [3], [15]). A method for a secondary node to estimate its MIFTP is developed in [3] for the case of a single primary transmitter; the multiple transmitter case is addressed in [16].

In [7], joint spatial-temporal sensing is proposed for one PT with a single channel at frequency f. The joint spatial-temporal sensing in [7] can easily be extended to multichannel scenario. In particular, at the beginning of each transmission frame, a set of secondary nodes collaboratively estimates the ON/OFF state of PT i by switching to channel f_i using temporal sensing algorithms proposed in [7]. Spatial spectrum holes on channel i in terms of MIFTP can be estimated by a group of secondary users switching to frequency f_i. We assume that the MIFTP of a secondary user on channel f_i remains unchanged until the location of PT i changes.

Both spatial sensing and temporal sensing over N cognitive channels can be performed concurrently by using N sets of temporal or spatial sensing nodes or sequentially by one set of temporal or spatial sensing nodes that sequentially switch among the N channels. In practice, the time scale over which the PT changes its location is much larger than the time scale of its ON/OFF durations. Under this assumption, the extra overhead of joint spatial-temporal sensing compared to temporal sensing is not significant.

For a given PT i with frequency f_i, the wireless channel is modeled by Rayleigh fading with time correlation [17]. We assume that the channel remains constant for a duration of $N_s/2$ symbols. For the first half of the transmission frame, the received signal of a simple wireless channel model with flat (frequency non-selective) fading without shadowing is given by [18]

$$y_1 = \sqrt{P(d,\epsilon)} h_i s_1 + n_1, \tag{1}$$

where

$$P(d,\epsilon) \triangleq \delta^2 \left(\frac{d_0}{d}\right)^{\alpha} \epsilon$$

denotes the equivalent transmitted power after taking into account the effect of path loss. Here, δ^2 is the free space signal power attenuation factor between the source and a reference distance d_0, d is the distance between the source and destination, α is the propagation exponent, $h \sim \mathcal{CN}(0,1)$ is a complex Gaussian random variable with variance 1, $n_1 \sim \mathcal{CN}(0, N_0)$, and s_1 is the transmitted signal.

For the second half of the frame, we have

$$y_2 = \sqrt{P(d,\epsilon)} g_i s_2 + n_2, \tag{2}$$

where

$$g_i = \rho_i h_i + \sqrt{1-\rho_i^2}\alpha_i \tag{3}$$

where $\alpha_i \sim \mathcal{CN}(0,1)$, $n_1 \sim \mathcal{CN}(0, N_0)$, and $\rho_i = J_0(2\pi D_i \tau)$ is the channel autocorrelation [17], where D_i is the Doppler shift of channel i and τ is the time to transmit $N_s/2$ symbols.

Let ϵ_i and $\tilde{\epsilon_i}$ denote the MIFTP of a given ST when PT i is ON and the maximum transmission power that can be used when PT i is OFF, respectively. We also define

$$P_i = P(d, \epsilon_i),\ \tilde{P}_i = P(d, \tilde{\epsilon_i}),$$

as the equivalent transmitted powers when PT i is ON from ST to a given secondary receiver (SR) when PT i is ON and OFF, respectively. To combat the low SNR at the SR due to limited transmit power at the ST, a repetition code is used at the ST. Note that the repetition code is close to optimal in the low SNR regime [19]. By using the repetition code, the ST transmits the same signal in both halves of the transmission frame, i.e., $s_1 = s_2 = s$. We also assume that the channel coefficients h_i and g_i can be estimated at the SR, i.e., via training sequences, and maximal ratio combining (MRC) is used to combine the received signal at the SR. Hence, the final received signal at SR is

$$y = \sqrt{P}(|h_i|^2 + |g_i|^2)s + h_i^* n_1 + g_i^* n_2 \quad (4)$$

where $P = P_i$ when PT i is ON and $P = \tilde{P}_i$ when PT i is OFF.

III. EXPLOITING MULTICHANNEL DIVERSITY

A. Randomized channel switching

Consider a simple scenario in which we have two communication pairs (ST 1, SR 1) and (ST 2, SR 2) over two cognitive radio channels with frequencies f_1 and f_2, respectively. When there is no channel switching, i.e., ST i uses the same channel f_i to communicate with SR i, the received signal at SR (cf. (4)) cannot achieve a diversity order of two because h_i and g_i are correlated. To exploit multichannel diversity during the first half of the frame, ST 1 uses channel f_1 to communicate with SR 1 and switches to channel f_2 during the second half of the frame. Thus, the received signal at SR 1 is

$$y = (\sqrt{\mu_1}|h_1|^2 + \sqrt{\mu_2}|g_2|^2)s + h_1^* n_1 + g_2^* n_2 \quad (5)$$

where $\mu_1 = P_1$ or $\mu_1 = \tilde{P}_1$ if PT 1 is ON or OFF, respectively. $\mu_2 = P_2$ or $\mu_2 = \tilde{P}_2$ if PT 2 is ON or OFF, respectively. Since h_1 and g_2 are independent, the received signal at SR 1 has diversity order two. Similarly, the received signal at SR 2 also has diversity order two.

We expect that the average symbol error probability (SEP) will decrease compared to the case when there is no channel switching. In the general scenario, we may have N channels with frequencies f_i and N pairs (ST i, SR i), $i = 1, 2, \ldots, N$. In this case, pair (ST i, SR i) can switch to channel $j \neq i$ during the second half of the transmission frame as long as there is no transmission on channel j. We assume that there is a centralized scheduler or a medium access control protocol to oversee the process of channel switching.

B. Performance Analysis

1) Randomized channel switching: Next, we analyze the performance of our scheme in term of average symbol error probability (SEP). Let p_i^{on} and p_i^{off}, respectively, denote the ON and OFF probabilities of PT i, $i = 1, 2$. We shall assume that M-PSK modulation is used. Using the moment generating function (MGF) approach in [20], [21], the SEP of M-PSK signals with MRC of L independent fading paths can be expressed as

$$\frac{1}{\pi}\int_0^{\frac{(M-1)\pi}{M}} \prod_{k=1}^{L} M_{\gamma_k}\left(-\frac{g_{\text{PSK}}}{\sin^2\phi}\right) \mathrm{d}\phi \quad (6)$$

where $g_{\text{PSK}} = \sin^2(\pi/M)$ and $M_{\gamma_l}(u) = (1 - u\bar{\gamma}_l)^{-1}$ is the moment generating function of Rayleigh fading with average SNR γ_l.

Let $\mathbf{\Gamma} = (\gamma_1, \gamma_2, \ldots, \gamma_L)$ denote a vector of L average SNR values corresponding to L independent fading paths. Then the SEP can be expressed as

$$\psi(\mathbf{\Gamma}) = \frac{1}{\pi}\int_0^{\frac{(M-1)\pi}{M}} \prod_{k=1}^{L} \left(1 + \frac{g_{\text{PSK}}}{\sin^2\phi}\gamma_k\right)^{-1} \mathrm{d}\phi. \quad (7)$$

The received signal in (5) is the maximal ratio combining of two independent Rayleigh fading channel. Using the MGF approach, the SEPs for the four possible joint of PT 1 and 2 are given by

$$\begin{aligned}
\text{SEP}_{\text{on,on}} &= \psi(\gamma_1, \gamma_2),\\
\text{SEP}_{\text{on,off}} &= \psi(\gamma_1, \tilde{\gamma_2}),\\
\text{SEP}_{\text{off,on}} &= \psi(\tilde{\gamma_1}, \gamma_2),\\
\text{SEP}_{\text{off,off}} &= \psi(\tilde{\gamma_1}, \tilde{\gamma_2}).
\end{aligned}$$

The average SEP of the randomized switching scheme over all ON and OFF states of PT 1 and PT 2 is given by

$$\begin{aligned}
\overline{\text{SEP}}_{\text{rand}} = {}& p_1^{\text{on}} p_2^{\text{on}} \text{SEP}_{\text{on,on}} + \text{p}_1^{\text{on}} \text{p}_2^{\text{off}} \text{SEP}_{\text{on,off}} \quad (8)\\
&+ p_1^{\text{off}} p_2^{\text{on}} \text{SEP}_{\text{off,on}} + \text{p}_1^{\text{off}} \text{p}_2^{\text{off}} \text{SEP}_{\text{off,off}}.
\end{aligned}$$

In the case of pure spatial sensing, ST 1 and 2 always transmit with at their MIFTPs, so the average SEP in this case is simply $\text{SEP}_{\text{on,on}}$.

2) No channel switching: When there is no channel switching, the received signal at the SR is given by (4). As $h_i \sim \mathcal{CN}(0, 1)$, we can denote $h_i = a_i + jb_i$ where $a_i, b_i \sim \mathcal{N}(0, 0.5)$. In (3), let $\alpha_i = c_i + jd_i$ where $c_i, d_i \sim \mathcal{N}(0, 0.5)$. The term $|h_i|^2 + |g_i|^2$ in (4) can be rewritten as

$$\begin{aligned}
|h_i|^2 + |g_i|^2 = {}& (1 + \rho^2)(a_i^2 + b_i^2) + (1 - \rho^2)(c_i^2 + d_i^2)\\
&+ 2\rho\sqrt{1 - \rho^2}(a_i c_i + b_i d_i).
\end{aligned}$$

We have $E[(a_i c_i + b_i d_i)] = 0$ where $E[\cdot]$ denotes the expectation operator. Hence, we can approximate

$$|h_i|^2 + |g_i|^2 \approx (1 + \rho^2 - \delta)(a_i^2 + b_i^2) + (1 - \rho^2)(c_i^2 + d_i^2), \quad (9)$$

where the constant δ accounts for the fact that when the term $a_i c_i + b_i d_i$ is negative, the received SNR is effectively reduced, resulting in erroneous symbol detection. An appropriate value of δ can be determined by computer simulation. We find

$$\delta = \begin{cases} \rho^2(1 - \rho), & \text{if } \rho < 0.7,\\ \rho(1 - \rho), & \text{if } \rho \geq 0.7. \end{cases} \quad (10)$$

Combining (9) and (4), we have

$$y_a \approx \sqrt{P}\big[(1 + \rho^2 - \delta)|h_i|^2 + (1 - \rho^2)|\alpha_i|^2\big]s + z, \quad (11)$$

where $z = h_i^* n_1 + g_i^* n_2$. The received signal y_a in (11) can be approximated by the maximal ratio combination of two independent channels with Rayleigh fading coefficients h_i and α_i and average SNRs $\gamma_1 = P(1 + \rho^2 - \delta)/N_0$ and $\gamma_2 = P(1 - \rho^2)/N_0$. Finally, the average SEP at the secondary receiver when there is no channel switching is

$$\text{SEP}_{\text{conv}} = \psi(\gamma_1, \gamma_2). \quad (12)$$

Our analysis is confirmed by simulation results presented in Section V.

IV. MAXIMIZED SNR SCHEDULING ALGORITHM

In this section, we propose a scheduling algorithm that exploits multichannel diversity in cognitive radio networks. Our scheduling algorithm maximizes the SNR of the received signal at the SR. We assume that N cognitive channels with frequencies f_i, $i = 1, 2, \ldots, N$ allow simultaneously transmission of up to N pairs of (ST, SR). Let $K \leq N$ be the number of concurrent secondary transmission. We also assume that the scheduler knows the ON/OFF state of PT i. The scheduler maintains a state vector $\mathbf{p}$ whose ith component $p(i) = 1$ when PT i is OFF and $p(i) = 0$ when PT i is ON.

Through spatial sensing, scheduler can obtain an estimate of the distance between ST i and SR i and therefore an estimate of the equivalent transmitted powers P_i and $\tilde{P}_i$. The scheduler also has the knowledge of the channel state information (CSI) matrix $\mathbf{H}$ at the beginning of each transmission frame. The CSI matrix $\mathbf{G}$ is also available at the second half of the transmission frame. These CSI matrices can be estimated at the SR via training and then forwarded to the scheduler. The elements of the channel matrix $\mathbf{H}$, $H(i,j) = h_{ij}$, where $1 \leq i \leq N$ and $1 \leq j \leq K$ and h_{ij} is the channel gain between ST j and SR j on channel i for the first half of the transmission frame. The (i,j) element of the channel matrix $\mathbf{G}$, $G(i,j) = g_{ij}$, is the channel gain between ST j and SR j on channel i for the second half of the transmission frame. We have

$$g_{ij} = \rho_{ij} h_{ij} + \sqrt{1 - \rho_{ij}^2}\,\alpha_{ij}$$

where ρ_{ij} is the channel autocorrelation between ST j and SR j on channel i and $\alpha_{ij} \sim \mathcal{CN}(0, 1)$.

The scheduler also maintains an idle/reserved channel status matrix $\mathbf{S}$ of dimension $N \times 2$, where $S(i, 1) = 0$ if the first half of transmission frame of channel i is idle, otherwise $S(i, 1) = 1$, i.e., the first half of transmission frame of channel i is reserved for transmission. We also have $S(i, 2) = 0$ if the second half of transmission frame of channel i is idle; otherwise $S(i, 2) = 1$, i.e., the second half of transmission frame of channel i is reserved for transmission.

At the beginning of the transmission frame, Algorithm 1 starts with user 1. It finds the channel k in the list of N available channels such that the received SNR γ_k is maximized, where $\gamma_k = P_k|h_{k1}|^2/N_0$ if PT is ON and $\gamma_k = \tilde{P}_k|h_{k1}|^2/N_0$ if PT is OFF. After channel k is reserved for user 1, it is removed from the list of available channels. The algorithm then proceeds to user 2 and repeats with the list of $N - 1$ remaining channels. The algorithm continues until all of the users have been scheduled.

Thus, the number of idle channels for user K is $N - K + 1$ because $K - 1$ channels have been reserved for $K - 1$ previous users. Because of the multichannel fading diversity, the larger the number of idle channels, the larger γ_k can be obtained. Clearly, in this algorithm, the first user has the most advantage. Therefore, to ensure fairness among users, in the next transmission frame, Algorithm 1 starts with user 2 and ends with user 1. After completing the scheduling task, i.e., $\mathbf{S}_1$ is identified, ST k uses channel $S_1(k)$ to transmit to SR k. The same algorithm is used for the second half of the transmission frame. The performance of the maximized SNR scheme is expected to outperform that of the simple randomized channel switching scheme in Section III. This is confirmed by numerical results given in Section V.

Algorithm 1 Maximized SNR scheduling algorithm

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Input: ON/OFF state vector $\mathbf{p}$, CSI matrices $\mathbf{H}$ and $\mathbf{G}$, idle/reserved matrix $\mathbf{S}$
for $j = 1$ to $K$ do
    $t \leftarrow 0$
    while $t < K$ do
        $k \leftarrow j + t \mod K$
        $\mathbf{S} \leftarrow \mathbf{0}$
        if (First half of transmission frame) then
            $S_1(k) \leftarrow \arg\max_{i, S(i,1)=0}\{(\gamma_i + p(i)(\tilde{\gamma}_i - \gamma_i))|h_{ij}|^2\}$
            $S(S_1(k), 1) \leftarrow 1$
        else if (Second half of transmission frame) then
            $S_2(k) \leftarrow \arg\max_{i, S(i,2)=0}\{(\gamma_i + p(i)(\tilde{\gamma}_i - \gamma_i))|h_{ij}|^2\}$
            $S(S_2(k), 2) \leftarrow 1$
        end if
        $t \leftarrow t + 1$
    end while
end for
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V. NUMERICAL RESULTS

In this section, we compare the SEP performance of the different schemes. For all simulations, we use BPSK modulation and a frame length of $N_s = 640$ symbols. All channels have the same P_i and $\tilde{P}_i$. The average SNR $\gamma_i = P_i/N_0$ and $\tilde{\gamma}_i = \tilde{P}_i/N_0$. We assume that $\tilde{\gamma}_i = \gamma_i + 10$ dB and in all figures $\mathrm{SNR} = \gamma_\mathrm{i}$. Except for Fig. 4, the ON/OFF probabilities of a PT are assumed to be the same across all channels, i.e., $p_i^{\mathrm{on}} = p_i^{\mathrm{off}} = 0.5$.

In Fig. 2, we compare the performance of our randomized channel switching scheme with a conventional scheme with no channel switching. We assume all channels have the same correlation $\rho = 0.8$. As seen in Fig. 2, the randomized channel switching scheme effectively reduces the average SEP. For spatial sensing, the randomized channel switching scheme is about 3 dB better in the SEP range of interest, i.e., $\mathrm{SEP} \leq 10^{-3}$, than the conventional scheme. For joint spatial-temporal sensing, the random switching scheme is about 4 dB better than the conventional scheme. For joint spatial-temporal sensing, randomized channel switching exploits both fading diversity and the diversity of the ON/OFF state of the PT. Clearly, joint spatial-temporal sensing always outperforms spatial sensing for a given switching scheme. In Fig. 2, the simulation and analytical results derived in Section III-B are closely matched.

In Fig. 3, we compare the SEP of the conventional scheme with randomized channel switching over different values of the channel correlation $\rho_1 = \rho_2 = \rho$. We use $\gamma_i = 12$ dB and

$\tilde{\gamma}_i = 22$ dB with $i = 1, 2$. As in Fig. 3, the performance of randomized channel switching is not affected by the channel correlation because the ST switches to a new channel with independent channel fading. The SEP of the conventional scheme increases as ρ increases. At $\rho = 0$, i.e., no correlation, under pure spatial sensing, the SEP of the conventional scheme equals that of the randomized channel switching scheme. However, at $\rho = 0$, the randomized channel switching still outperforms the conventional scheme when joint spatial-temporal sensing is used. The reason is that even when $\rho = 0$, random switching can exploit multichannel diversity in terms of the ON/OFF diversity of the PT. In particular, low received SNR normally occurs when both PTs are ON for joint spatial-temporal sensing, i.e., with probability $p_1^{\text{on}} p_2^{\text{on}}$, and when PT 1 or PT 2 is ON, i.e., with probabilities p_1^{on} or p_2^{on}, respectively.

Next, we investigate scenarios in which two channels have different p^{off} probabilities in Fig. 4: $p_1^{\text{off}} = 0.8$ and $p_2^{\text{off}} = 0.4$, respectively. Clearly, if user 1 always uses channel 1 and user 2 always uses channel 2, the performance experienced by user 1 will always be better than that by user 2. As p^{off} increases, the probability that the ST can transmit with maximum power increases, and thus the performance improves. This may create fairness issues in multichannel cognitive radio networks. However, by employing randomized switching, both users will have the same performance. Also, in the SEP range of interest, i.e., $\text{SEP} \leq 10^{-3}$, the performance of randomized channel switching is equal or even better compared to the performance of user 1 when there is no channel switching. Randomized channel switching not only improves performance but also guarantees fairness among the secondary users.

In Fig. 5, we compare the performance of the randomized channel switching scheme in conjunction with the maximized SNR scheduling scheme of Algorithm 1. In maximized SNR scheduling, the total of $N = 4$ channel is used. When SEP $=10^{-5}$, Algorithm 1 with $K = 4$ concurrent (ST,SR) transmissions performs about 10 dB better than randomized channel switching. As the number of concurrent transmissions, K, decreases, the average SEP decreases. When $K = 1$, the maximizing SNR scheduling scheme is about 13 dB better than randomized channel switching and about 3 dB better than maximized SNR scheduling with $K = 4$.

In Fig. 6, we investigate the performance of maximized SNR scheduling as the number of channels N increases. We assume $K = 1$ and all channels have $\rho = 0.8$. We also assume that $\gamma_i = 4$ dB and $\tilde{\gamma}_i = 14$ dB. The simulation results show that the SEP of our proposed scheduling scheme decreases significantly as the total number of users N increases. When more channels are available, the maximized SNR of all channels increases and hence, the performance of maximized SNR scheduling improves.

VI. CONCLUSION

We considered a multichannel cognitive radio network with joint spatial-temporal spectrum sensing. In a multichannel cognitive radio network, fading diversity exists among different channels at a given time. We showed that simple randomized switching among different channels during transmission significantly improves the performance of cognitive transmission. When the channel fading coefficients and the ON/OFF states of all primary transmitters are available, the proposed maximized SNR algorithm further improves transmission performance. In this paper, our performance analysis was based on average symbol error probability. In ongoing work, we are investigating the achievable capacity of our proposed schemes.

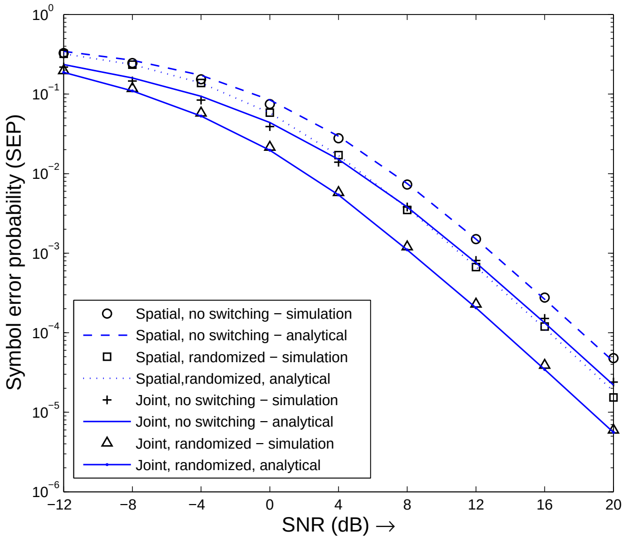

Fig. 2. Performance of randomized channel switching.

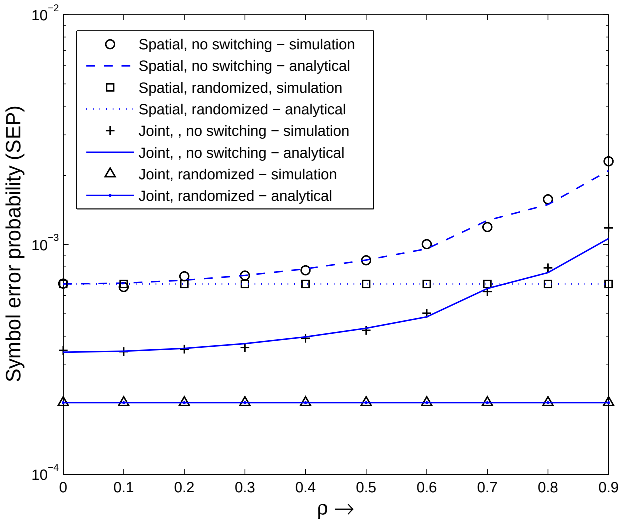

Fig. 3. Performance of different schemes over ρ.

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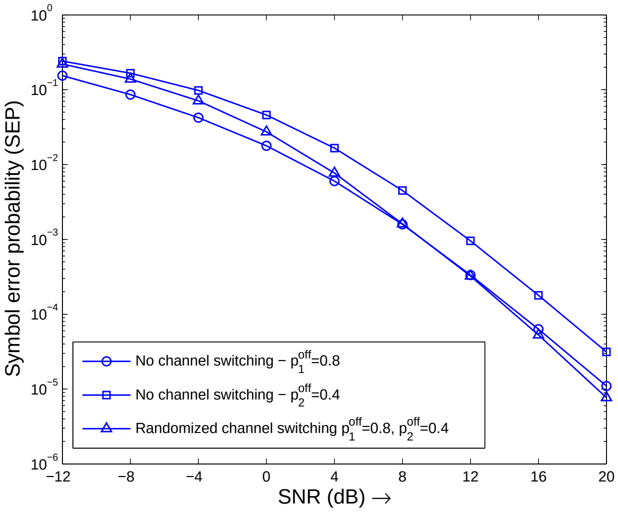

Fig. 4. Randomized channel switching and user's fairness.

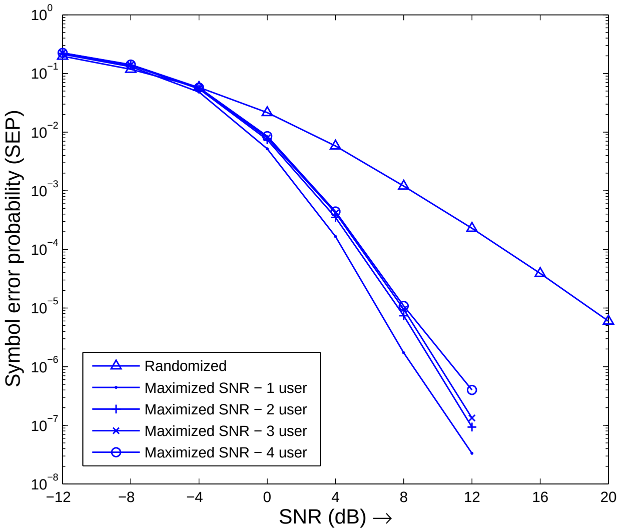

Fig. 5. Performance of maximized SNR scheduling.

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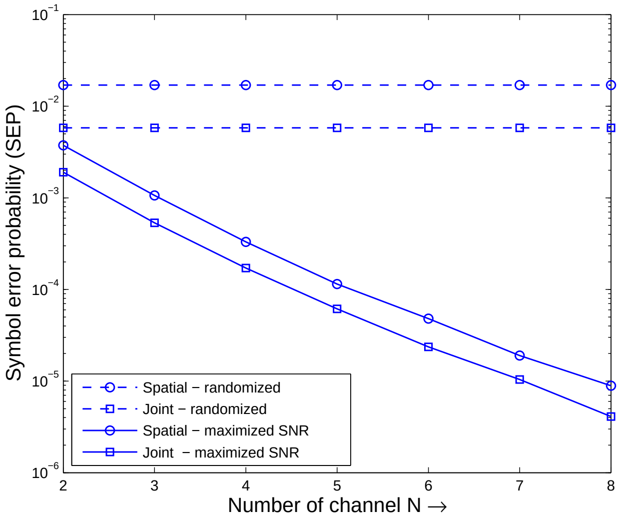

Fig. 6. Performance of maximized SNR scheduling over N.

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