On the Performance of Relay Selection in Cognitive Radio Networks

Zoubeir Mlika *, Wessam Ajib *, Wael Jaafar † and David Haccoun †
* Department of Computer Science, Université du Québec à Montréal
mlika.zoubeir@gmail.com, ajib.wessam@uqam.ca
† Department of Electrical Engineering, École Polytechnique de Montréal
{wael.jaafar, david.haccoun}@polymtl.ca

***Abstract*—In this paper, we investigate several relaying schemes for cooperative communications in Cognitive Radio Networks (CRNs) in order to improve the performances of secondary transmissions while respecting a certain Quality of Service (QoS) requirement at the primary transmissions. We propose relaying schemes where a number of relay nodes, randomly located, may help either the primary or the secondary transmission. By defining proper relay selection criteria and power allocation schemes, we illustrate the secondary outage probability performance while guaranteeing the primary QoS. Using simulations, we present the impact of different parameters, such as the QoS requirement, the chosen relay selection criteria, the number of available relays, the positions of the relays, etc., on the secondary transmission performance. The obtained results show the potential of the proposed relaying schemes, and provide guidelines about the expected secondary performance under the impact of several parameters.**

I. Introduction

Recently, Cognitive Radio Networks (CRNs) are being considered as a new paradigm in wireless networks that can improve the utilization of the electromagnetic spectrum [1]. In some types of CRNs, we usually have unlicensed secondary users (SUs) using some frequency bands devoted to licensed primary users (PUs). PUs and SUs can co-exist and operate in the same frequency band under the constraint that the interference perceived by the primary users and caused by the secondary users is limited, i.e. the quality of service (QoS) required by the primary transmission is guaranteed [2]. Therefore, SUs must have a limited transmit power which implies limited transmission performances. Also, user cooperative diversity transmission is being used as a new technique to form virtual antenna arrays, i.e. without using multiple antennas at each transceiver in order to obtain a diversity gain [3], [4]. This emerging technique was shown to provide dramatic gains in slow fading environments. But, they come at the expense of a reduction in the spectral efficiency since the relay nodes transmit on orthogonal channels to prevent interfering one another.

To address this problem, some relay selection algorithms, that necessitate only two channels (the direct channel and the "best" relay channel), are used in the literature. It has been shown in [5], [6] that relay selection algorithms can achieve the same diversity gain as the one achieved by traditional cooperation schemes that use all the available relays. Moreover, cooperation has a great potential to be used in CRNs. In [7], the authors have studied the power allocation and the diversity when assisting the secondary transmissions, and have shown the secondary outage performance gain compared to non-cooperative transmissions. The authors in [8] proposed a cooperative scheme for primary transmissions. They showed that the secondary access to the licensed spectrum bandsmay be improved. In [9], the authors have explored an adaptive cooperative scheme with best-relay selection using fixed secondary relay nodes and have provided its performance gain in terms of secondary outage probability. In [10], the authors have used a single relay node to assist opportunistically both primary and secondary transmissions. They showed that a significant improvement in the secondary performance can be obtained compared to other schemes presented in the literature.

The main contributions of this paper are the proposition and the investigation of several relaying schemes for cooperative transmissions in CRNs, where multiple cognitive relay nodes are randomly distributed in a specific geographic area and where each relay may help the secondary or the primary transmission. We illustrate the secondary outage performance under the impact of different parameters, such as the required primary QoS, the chosen relay selection criteria, the number of available relay nodes, etc. These results provide guidelines about the expected performance of cooperative communications in CRNs.

The paper is organized as follows. The system model and transmission process are defined in Section II. Section III illustrates our proposed relay selection schemes for cooperative transmissions in CRNs. Section IV shows the simulation results and provides some discussions. Finally, we conclude the paper in Section V.

II. System Model

We consider a CRN where a secondary transmission may coexist simultaneously on the same channel at the same time with a primary transmission. We assume that the primary and secondary transmissions follow the same time division access. Hence, new secondary transmissions are scheduled on the same time as primary transmissions. The primary transmitter, primary receiver, secondary transmitter and secondary receiver are denoted PT, PR, ST and SR respectively. The distance between nodes i and j is denoted $d_{i,j}$. The distance $d_{PT,PR}$ (which is equal to $d_{ST,SR}$) is defined as the unit distance.

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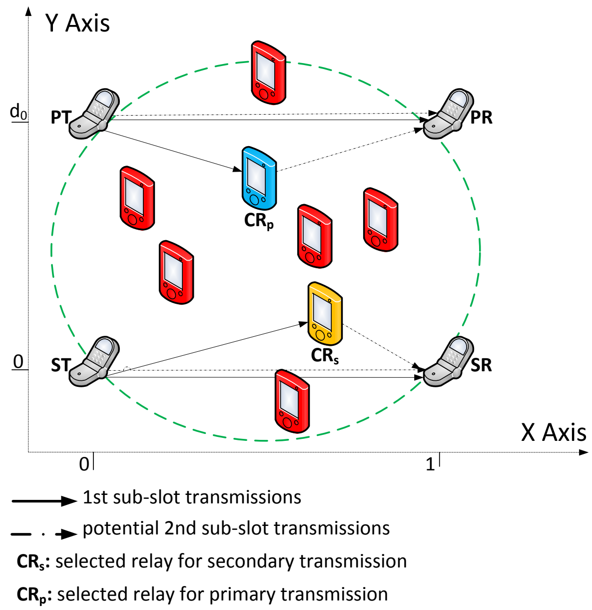

Fig. 1. Cooperative primary and secondary transmissions

As shown in Fig. 1 and without loss of generality, nodes ST, SR, PT and PR are assumed located at $(0,0), (1,0), (0,d_0)$ and $(1,d_0)$ respectively where $d_0 = d_{PT,ST} = d_{PR,SR}$. We assume the existence of M cognitive relay nodes, denoted CR_m where $m = 1,\dots,M$, randomly distributed in a circle with a center located at the coordinates $(1/2, d_0/2)$ and a diameter of $\sqrt{1+d_0^2}$. The primary transmission and/or the secondary one can be assisted by one of the relay nodes (see Fig. 1) using the Decode-and-Forward protocol [3].

We consider an aggregate channel model which takes into account both path loss and slow Rayleigh fading. The channel gain between nodes i and j is modeled as $h_{i,j} = \sqrt{d_{i,j}^{-\alpha}} \times g_{i,j}$ where α is the path loss coefficient and $g_{i,j}$ is the fading coefficient modeled as a zero-mean, complex Gaussian random variable with unit variance. We assume that the cognitive relays perform perfect spectrum sensing and has a perfect knowledge of the different channel states, whereas the ST has the information related to the primary and secondary channels. These information could be obtained in a stationary network by using limited feedback transmissions.

Time is divided into slots and each one is divided into two sub-slots corresponding to two transmission phases (see Fig. 1). The fading coefficient is assumed fixed during one slot and varies independently with each time slot. In the first sub-slot, ST and PT transmit their data. The received signals $(y_{PR}(1), y_{SR}(1)$ and y_{CR_m} $m = 1,\dots,M)$ are given by:

$$y_a(1) = \sqrt{P_{PT}} h_{PT,a} x_p + \sqrt{P_{ST}} h_{ST,a} x_s + n_a, \tag{1}$$

where a=PR, SR or CR$_m$, x_p and x_s $(E[|x_p|^2] = E[|x_s|^2] = 1)$ are the primary and secondary signals, P_{PT} and P_{ST} are the primary and secondary transmit powers used at the first sub-slot, and n_a represents the Additive White Gaussian Noise (AWGN) with zero mean and power spectral density N_0 received at a (a=PR, SR or CR$_m$). The QoS required by the PU is that its outage probability, $P_{out_{pri}}$, must be lower than a given threshold denoted ϵ [9]: i.e.,

$$P_{out_{pri}} \leq \epsilon. \tag{2}$$

All CR_m $(m = 1,\dots,M)$ attempt to decode the received signals in order to cooperatively help either the primary or the secondary transmission. The set of relays able to decode successfully the primary (or secondary) signal is denoted the primary (or secondary) decoding set D_P (or D_S respectively). Hence, D_P contains all the relays $CR_m^{(p)}$ that verify [9]:

$$\frac{1}{2}\log_2\left(1 + \frac{P_{PT}|h_{PT,CR_m^{(p)}}|^2}{P_{ST}|h_{ST,CR_m^{(p)}}|^2 + N_0}\right) \geq R_P, \tag{3}$$

and D_S contains the relays $CR_m^{(s)}$ that verify:

$$\frac{1}{2}\log_2\left(1 + \frac{P_{ST}|h_{ST,CR_m^{(s)}}|^2}{P_{PT}|h_{PT,CR_m^{(s)}}|^2 + N_0}\right) \geq R_S, \tag{4}$$

where R_P and R_S are the primary and secondary data rates. Note that sets D_P and D_S may not be disjoint.

Lemma 1: $CR_m \in D_P \cap D_S$ if and only if:

$$\Theta_P \Theta_S < 1. \tag{5}$$

Proof: Suppose that a relay CR_m verifies (3)-(4). Thus,

$$\left(\frac{x}{y+1}\right) \geq \Theta_P \text{ and } \left(\frac{y}{x+1}\right) \geq \Theta_S \quad \Leftrightarrow x \geq \frac{\Theta_P\Theta_S + \Theta_P}{1 - \Theta_P\Theta_S}, \tag{6}$$

where $x = \frac{P_{PT}}{N_0}|h_{PT,CR_m}|^2$, $y = \frac{P_{ST}}{N_0}|h_{ST,CR_m}|^2$, $\Theta_P = 2^{2R_P} - 1$ and $\Theta_S = 2^{2R_S} - 1$. Since x is exponentially distributed with parameter $P_{PT} d_{PT,CR_m}^{-\alpha}/N_0$, then:

$$\begin{aligned} P\left\{x \geq \frac{\Theta_P(\Theta_S+1)}{1-\Theta_P\Theta_S}\right\} &= e^{-\frac{(\Theta_P(\Theta_S+1))N_0}{(1-\Theta_P\Theta_S)P_{PT}d_{PT,CR_m}^{-\alpha}}} \leq 1 \\ \Leftrightarrow \Theta_P\Theta_S &< 1. \end{aligned} \tag{7}$$

This completes the proof of Lemma.1. ■

If D_P (or D_S resp.) contains only one relay (called R) that belongs also to the other set and if D_S (or D_P resp.) contains more than one relay, then the relay R is removed from the set D_S (or D_P resp.) in order to increase the probability that both transmissions are relayed.

In the second sub-slot, a selected relay from D_P (if available) may forward the decoded primary signal and a selected relay from D_S (if available) may forward the secondary signal. Then, after normalizing the noise variances, Maximum Ratio Combining (MRC) is used to combine the signals received at each destination. Finally, Maximum Likelihood Decision (MLD) is used to estimate each signal.

III. Proposed Relay Selection Schemes for Cooperative Transmissions in Cognitive Radio Networks

A. Relay Selection

A relay node is selected from each decoding set in order to cooperate with the primary and the secondary transmissions.

We start by selecting the relay CR_S (if available) to help the secondary transmission and then, we select CR_P (if available) that will cooperate with the primary transmission. We present four selection criteria as follows:

1) *Random selection:* the relay is randomly selected.
2) *Channel gain selection:* CR_P (if available) verifies: $P = arg \max_{p \in D_P} |h_{CR_p,PR}|^2$. Similarly, CR_S (if available) verifies: $S = arg \max_{s \in D_S} |h_{CR_s,SR}|^2$.
3) *Relative channel gain selection:* the selected relay, CR_P, (if available) verifies: $P = arg \max_{p \in D_P} \frac{|h_{CR_p,PR}|^2}{d_{CR_p,SR}^{-\alpha}}$, and CR_S (if available) verifies: $S = arg \max_{s \in D_S} \frac{|h_{CR_s,SR}|^2}{d_{CR_s,PR}^{-\alpha}}$.
4) *Average relative channel gain selection:* CR_P, (if available) verifies: $P = arg \max_{p \in D_P} \frac{d_{CR_p,PR}^{-\alpha}}{d_{CR_p,SR}^{-\alpha}}$ and CR_S (if available) verifies: $S = arg \max_{s \in D_S} \frac{d_{CR_s,SR}^{-\alpha}}{d_{CR_s,PR}^{-\alpha}}$.

B. Power allocation

We consider a simple power allocation scheme to illustrate the benefits of our relay selection schemes. More adaptive power control schemes (e.g., [11]) could also be considered. We assume a fixed primary transmit power P_{PT} in the first sub-slot. Meanwhile, P_{ST} is calculated such that (2) can be respected. Note that the primary outage probability depends on whether the relays will cooperate with the primary or the secondary transmissions or not. Hence, P_{ST} is calculated assuming that no relay will help neither the primary nor the secondary transmissions in the second sub-slot. In this case, PT and ST will retransmit their signals and the primary outage probability is given by:

$$\begin{aligned} P_1 &= P_{pri}(out|D_P = \emptyset, D_S = \emptyset) \\ &= Prob\left(\frac{2P_{PT}|h_{PT,PR}|^2}{P_{ST}|h_{ST,PR}|^2 + N_0} \leq \Theta_P\right) < \epsilon. \end{aligned} \tag{8}$$

We have $|h_{i,j}|^2 = d_{i,j}^{-\alpha}|g_{i,j}|^2$ and the random variable $x_{i,j} = |g_{i,j}|^2$ follows an exponential distribution with parameter 1 (i=PT or ST; j=PR or SR). Thus, using the probability density function (PDF) of $x_{i,j}$, we get:

$$\begin{aligned} P_1 &= \int_0^\infty \int_0^{z(y)} e^{-(x+y)} dx dy \\ &= 1 - \frac{2\alpha_{PT,PR} e^{-\frac{\Theta_P}{2\alpha_{PT,PR}}}}{\alpha_{ST,PR}\Theta_P + 2\alpha_{PT,PR}}, \end{aligned} \tag{9}$$

where $z(y) = \frac{\Theta_P(y\alpha_{ST,PR}+1)}{2\alpha_{PT,PR}}$ and $\alpha_{i,j} = \frac{P_i d_{i,j}^{-\alpha}}{N_0}$. We can calculate the secondary transmit power P_{ST} by substituting (9) into (2):

$$P_{ST} = max\left\{0, \frac{2P_{PT}d_{PT,PR}^{-\alpha}}{\Theta_P d_{ST,PR}^{-\alpha}} \times \left[\frac{1}{1-\epsilon} e^{-\frac{\Theta_P}{2\alpha_{PT,PR}}} - 1\right]\right\}. \tag{10}$$

As we can see from (10), if the primary transmit power is lower than a certain cutoff value ($P_{PT} < P_{PT}^c$), then ST is not able to access the licensed band since P_{ST} is set to zero. The cutoff value is given by:

$$P_{PT}^c = \frac{-\Theta_p N_0}{2\ln(1-\epsilon)}. \tag{11}$$

In the following, we distinguish between four transmission scenarios according to the emptiness of the decoding sets. We present the received signals in the second sub-slot and the primary outage probability. We use the expressions of the primary outage probability in order to find the transmit powers in the second sub-slot similarly to (8)-(10).

1) $D_P = \emptyset$ and $D_S = \emptyset$: In this case, PT and ST retransmit their signals using the same transmit power used in the first sub-slot (P_{PT} and P_{ST}) and the primary outage probability is given by (9).

2) $D_P \neq \emptyset$ and $D_S = \emptyset$: ST retransmits its signal using P_{ST}; whereas, the selected relay ($CR_P \in D_P$) forwards the primary decoded signal using a new transmit power value P_{CR_P}. The received signals on the 2^{nd} sub-slot are:

$$y_a(2) = \sqrt{P_{CR_P}} h_{CR_P,a} x_p + \sqrt{P_{ST}} h_{ST,a} x_s + n_a, \tag{12}$$

where a=PR or SR. The power allowed to CR_P should be such that the following constraint is respected:

$$\begin{aligned} P_{pri} \quad & (out|D_P \neq \emptyset, D_S = \emptyset) = \\ Prob \quad & \left(\frac{P_{PT}|h_{PT,PR}|^2 + P_{CR_P}|h_{CR_P,PR}|^2}{P_{ST}|h_{ST,PR}|^2 + N_0} \leq \Theta_P\right) < \epsilon. \end{aligned} \tag{13}$$

The analytical expression of (13) is given in [10]. Hence, P_{CR_P} is calculated accordingly.

3) $D_P = \emptyset$ and $D_S \neq \emptyset$: PT retransmits its signal using P_{PT}; meanwhile, the selected relay ($CR_S \in D_S$) forwards the secondary decoded signal using transmit power value P_{CR_S}. The received signals are:

$$y_a(2) = \sqrt{P_{PT}} h_{PT,a} x_p + \sqrt{P_{CR_S}} h_{CR_S,a} x_s + n_a, \tag{14}$$

where a=PR or SR. P_{CR_S} should be chosen with respect to:

$$\begin{aligned} & P_{pri}(out|D_P = \emptyset, D_S \neq \emptyset) = Prob \\ & \left(\frac{P_{PT}|h_{PT,PR}|^2}{P_{ST}|h_{ST,PR}|^2+N_0} + \frac{P_{PT}|h_{PT,PR}|^2}{P_{CR_S}|h_{CR_S,PR}|^2+N_0} \leq \Theta_P\right) \quad < \epsilon. \end{aligned} \tag{15}$$

P_{CR_S} value is calculated as in [10].

4) $D_P \neq \emptyset$ and $D_S \neq \emptyset$: The received signals at the 2^{nd} sub-slot are:

$$y_a(2) = \sqrt{P_{CR_P}} h_{CR_P,a} x_p + \sqrt{P_{CR_S}} h_{CR_S,a} x_s + n_a, \tag{16}$$

where a=PR or SR. The selected relays should choose their transmit powers, P_{CR_P} and P_{CR_S}, such that:

$$\begin{aligned} & P_{pri}(out|D_P \neq \emptyset, D_S \neq \emptyset) = Prob \\ & \left(\frac{P_{PT}|h_{PT,PR}|^2}{P_{ST}|h_{ST,PR}|^2+N_0} + \frac{P_{CR_P}|h_{CR_P,PR}|^2}{P_{CR_S}|h_{CR_S,PR}|^2+N_0} \leq \Theta_P\right) \quad \leq \epsilon. \end{aligned} \tag{17}$$

Since (17) has two unknown parameters, we assume for simplicity that P_{CR_P} is equal to P_{CR_S}. Then, the relays' power $P_{CR_P} = P_{CR_S}$ is calculated numerically.

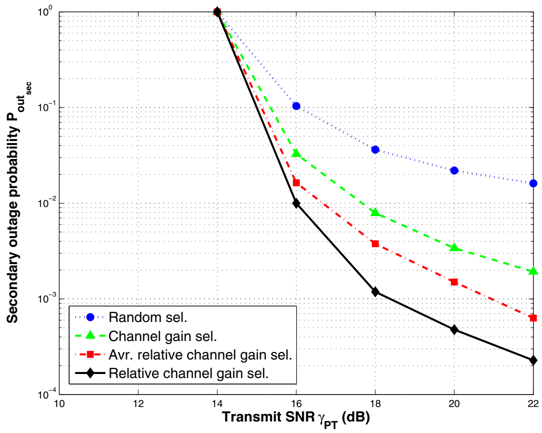

Fig. 2. $P_{out_{sec}}$ versus γ_{PT} for different selection criteria ($M = 6$)

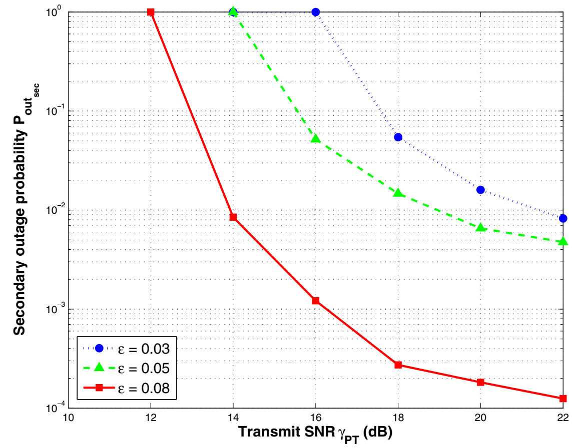

Fig. 3. $P_{out_{sec}}$ versus γ_{PT} for different thresholds ϵ ($M = 4$)

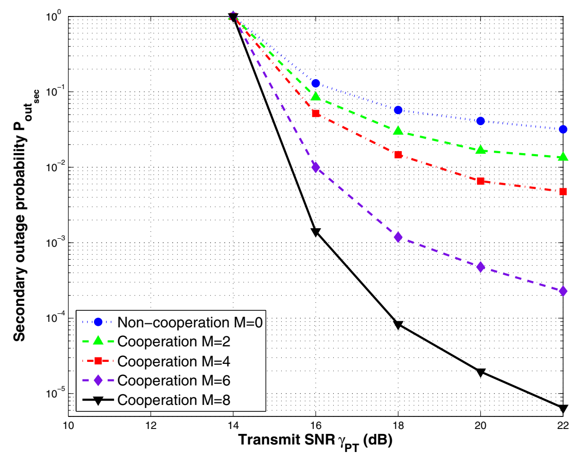

Fig. 4. $P_{out_{sec}}$ versus γ_{PT} for different M

IV. Simulation Results

In this section, we show the performance of our proposed relaying schemes in terms of outage probability. We present the secondary outage probability (denoted $P_{out_{sec}}$) versus the primary transmit Signal-to-Noise-Ratio (SNR) at PT ($\gamma_{PT} = P_{PT}/N_0$) using simulations, and we show the obtained gains. We assume $\alpha = 4$, $R_P = 1bps/Hz$, $R_S = 0.5bps/Hz$, $d_0 = 2$, $\epsilon = 0.05$, and the "relative channel gain sel." selection criteria unless otherwise is stated.

Fig. 2 illustrates the performance of the secondary transmission using different selection criteria. It is clear that the best criteria is the 4^{th} one when the relay is being selected according to the "relative channel gain sel.", that uses the ratio of the instantaneous channel gain to the PR (resp. SR) and the interference to SR (resp. PR). The "Avr. relative channel gain sel." gives a better performance compared to the "channel gain sel." since we consider the average interference of the relay CR_P (resp. CR_S) to SR (resp. PR). "The channel gain sel." does not have a good performance compared to the previous criterions. Indeed, the selection is based only on the best channel to the concerned destination without taking into account the generated interference at the other destination.

We notice that there is a cutoff value in terms of the primary transmit power, given by (11), below which there is no secondary transmissions and SUs have to seek for another opportunity to access the spectrum bands. As can be seen in Fig. 3, the secondary outage probability and the primary transmit power cutoff value could be improved by varying the primary outage threshold value ϵ. When ϵ increases (more tolerable primary QoS requirement), the secondary outage probability improves dramatically due to the increase of P_{ST}.

Fig. 4 shows the impact of the number of relay nodes M on the secondary outage probability. As M grows, the secondary outage performance enhances significantly. We also note that an outage probability floor occurs for high γ_{PT} values ($M = 0$). Indeed, when γ_{PT} is high, the interference from the primary transmission becomes the dominant factor to induce a channel outage. This floor disappears gradually as the number of relay nodes becomes larger, which illustrates the advantage of using relay selection.

Fig. 5 shows the performance of the secondary transmission while randomly varying the position of a single relay node in the area [PT, PD, SD, ST]. The best relay position is given between ST and SR and as soon as the relay moves away from ST and SR, the outage probability degrades. Specifically, we distinguish three distinct regions: close to the secondary system (region 1), close to the primary system (region 2), and between them (region 3). In region 1, the relay is able to help the secondary transmission rather than the primary one, then we get the best outage performance. When the relay is in region 2, it is able to assist the primary transmission rather than the secondary one. Therefore, the allocated power to the best relay will not create a serious problem to the secondary system and hence presents a reduction on the interference from the primary system. However, when moving from region 2 to region 3, $d_{CR_P,PR}$ increases. Then, CR_P has to increase its

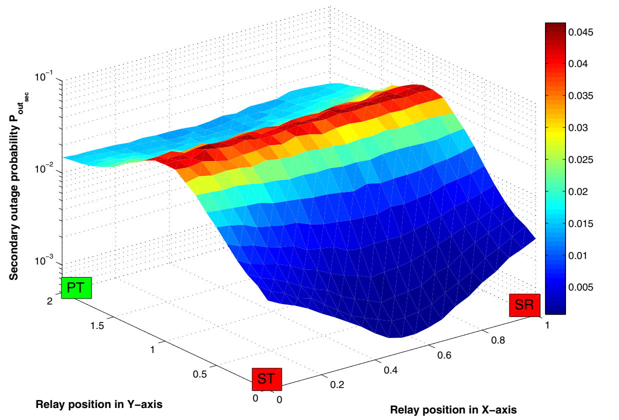

Fig. 5. $P_{out_{sec}}$ versus relay position in the plan (X, Y) ($\gamma_{PT} = 20dB$)

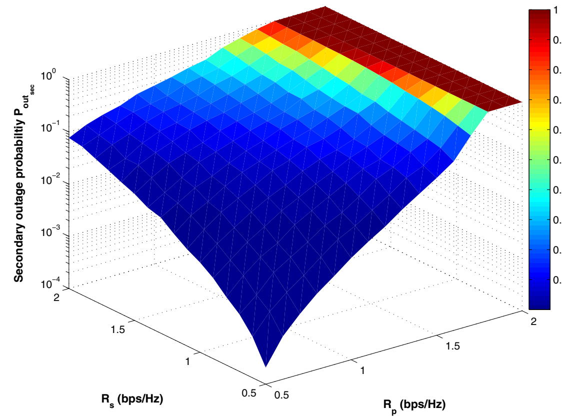

Fig. 7. $P_{out_{sec}}$ versus data rates R_P and R_S ($\gamma_{PT} = 20dB$ and $M = 4$)

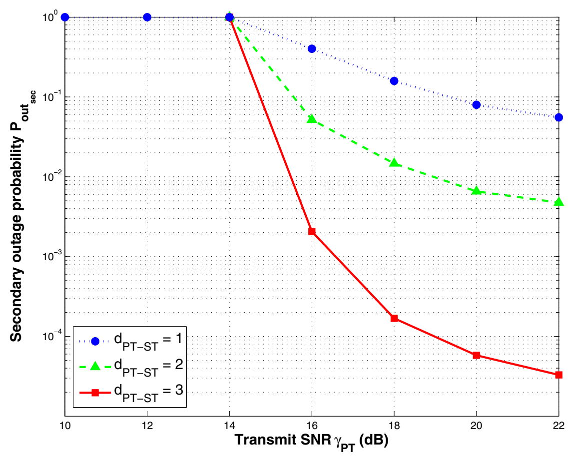

Fig. 6. $P_{out_{sec}}$ versus γ_{PT} for different distances between primary and secondary systems ($M = 4$)

transmit power and therefore causes more interference to the secondary system.

Fig. 6 presents the secondary performance versus the distance between the primary and the secondary systems. As $d_0 = d_{PT,ST} = d_{PR,SR}$ becomes larger, less interference is generated, and the secondary outage probability gets better.

Fig. 7 illustrates the impact of the variation of the data rates R_P and R_S on the secondary outage probability. The best performance is obtained for very low R_P and R_S. As R_P and/or R_S increases, the outage probability degrades severely. This is due to the nature of the CRN, that requires to satisfy the primary outage probability before allowing secondary transmissions.

V. Conclusion

In this paper, we investigate different relaying schemes for cooperative transmissions in CRNs, where available relay nodes are able to assist primary or secondary transmissions with respect to a primary QoS. We provide the outage probability gains obtained by the proposed relaying schemes, when relay nodes are randomly distributed in a specific geographic area, compared to the non-cooperative scheme. We find that by properly selecting cognitive relays to assist either the primary transmission, and/or the secondary one, the secondary outage probability is significantly improved. Finally, we investigate and evaluate the impact of many parameters on the secondary outage probability. The results provide guidelines about the expected performance of cooperative transmissions in CRNs.

References

[1] S. Haykin, "Cognitive radio: brain-empowered wireless communications," *IEEE J. Select. Areas Commun.*, vol. 23, no. 2, pp. 201 – 220, Feb. 2005.

[2] Y. Xing, C. N. Mathur, M. A. Haleem, R. Chandramouli, and K. P. Subbalakshmi, "Dynamic spectrum access with qos and interference temperature constraints," *IEEE Trans. Mobile Comput.*, vol. 6, no. 4, pp. 423 –433, Apr. 2007.

[3] J. Laneman, D. Tse, and G. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[4] W. Jaafar, W. Ajib, and D. Haccoun, "On the performance of multi-hop wireless relay networks," *Wireless Communications and Mobile Computing*, Dec. 2011, [Online] Available: http://www.wileyonlinelibrary.com.

[5] A. Bletsas, H. Shin, M. Z. Win, and A. Lippman, "A simple cooperative diversity method based on network path selection," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 3, pp. 659–672, Mar. 2006.

[6] S. Ikki and M. H. Ahmed, "Performance analysis of adaptive decode-and-forward cooperative diversity networks with best-relay selection," *IEEE Trans. Commun.*, vol. 58, no. 1, pp. 68–72, Jan. 2010.

[7] S. Kandukuri and S. Boyd, "optimal power control in interference-limited fading wireless channels with outage-probabiltiy specifications," *IEEE Trans. Wireless Commun.*, vol. 1, no. 1, pp. 46–55, Jan. 2002.

[8] O. Simeone, J. Gambini, Y. Bar-Ness, and U. Spagnolini, "Cooperation and cognitive radio," in *IEEE Int. Conf. on Commun., ICC*, June 2007, pp. 6511 –6515.

[9] Y. Zou, J. Zhu, B. Zheng, and Y.-D. Yao, "An adaptive cooperation diversity scheme with best-relay selection in cognitive radio networks," *IEEE Trans. Signal Process.*, vol. 58, no. 10, pp. 5438 –5445, Oct. 2010.

[10] W. Jaafar, W. Ajib, and D. Haccoun, "Opportunistic adaptive relaying in cognitive radio networks," in *IEEE Int. Conf. on Commun., ICC*, June 2012. [Online]. Available: http://arxiv.org/abs/1201.2937v1

[11] R. Zhang, "On peak versus average interference power constraints for protecting primary users in cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 8, no. 4, pp. 2112–2120, Apr. 2009.