Performance Evaluation of Cognitive Cooperative Radio Network Under Joint Constraints

Pham Huu Tung, Quach Xuan Truong, Vu Le Quynh Giang

***Abstract:** In this paper, we investigate outage performance of a cognitive cooperative underlay network in which secondary transmitter (SU-Tx) sends signals to the secondary receiver (SU-Rx) through the help of a single relay (SR). Here, we assume that the relay is equipped with multiple antennas and operates in the decode-and-forward mode. Furthermore, the relay uses the selection combining (SC)/transmit antenna selection (TAS) technique to process the signal. Given this setting, an adaptive transmit power allocation policy for the SU-Tx and SR are derived. Accordingly, simulations for the outage probability of the considered system is executed. Our numerical results will show the impact of different channel mean power gains between primary user and secondary user on the outage performance. Also, the impact of massive antennas at the SR on the performance of the considered system model is addressed.*

***Keywords:** Cognitive Cooperative Radio Networks, Outage Constraint, Peak Transmit Power, Device-to-Device Communication.*

I. INTRODUCTION

Recently, cognitive radio network (CRN) has been considered as a powerful technology to enhance the spectrum utilization and network performance in wireless communications [1]–[3] in which three main techniques, namely as spectrum underlay, spectrum overlay, and spectrum interweave, have been proposed to reutilize the temporarily unused spectrum resource. Wherein, the spectrum underlay approach has been received much attention from academia and industry. More specifically, in a spectrum underlay network, there exists two type of users named as primary user (PU) and secondary user (SU) in which PU licenses the spectrum while SU is allowed to simultaneously access the licensed spectrum of the PU as long as the interference from the SU does not interrupt the communication of the PU. To satisfy this constraint, the SU should have reasonable transmitted power to obtain high performance while keep the interference at the PU below a predefined threshold. Although spectrum underlay approach have many advan- tages, it have to face some challenges as follows: 1) The coverage range of the CRN is limited due to the interfer- ence constraints given by the PU. 2) Lack of channel state information between SU and PU may degrade the severe performance of the PU. 3) Low transmit power of the SU due to constraints of the PU leads to low transmission rate of the SU.

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To overcome these challenges, cognitive cooperative radio network (CCRN) is considered as a potential solution as it does not only extend the coverage range but also to provide reliable communication in spectrum underlay networks [4]–[17]. More specifically, a decode-and-forward (DF) scheme with best relay selection for a CCRN has been studied in [4], showing the impact of distances among secondary and primary users on the outage performance. In [14], authors have compare the capacity of proactive DF with the one of the reactive DF scheme under peak interference power constraint. In [5], subject to the outage constraint of the PU, an adaptive cooperation diversity scheme with best-relay selection has been proposed for a CCRN. In [17], we have analyzed the performance of a CCRN under the peak interference power constraints of multiple PU. The most recent work reported in [6] has derived the outage probability and ergodic capacity for a CCRN where the SUs are subject to the peak interference power constraint. Motivated by all of the above, in this paper, we use the joint outage constraint of the PU and peak transmit power constraint of the SU, which is different to all aforementioned works, to investigate the outage performance of a CCRN. In particular, we assume that the secondary transmitter (SU-Tx) commu- nicate with the secondary receiver (SU-Rx) through the help of a secondary relay (SR) in which the SR is equipped with multiple antennas. Given this context, an adaptive transmit power policies for the SU-Tx and SR are derived. Accordingly, the selection combining/transmit attenna selection (SC/TAS) is proposed for the considered system model, and then the system performance in terms of outage probability of the SC/TAS will be compared to the conventional selection combining (SC) technique. Simulation results will show a fact that the performance of the SC/TAS scheme outperforms the one of the SC scheme. To the best of our knowledge, there is no previous work addressing on this problem.

II. SYSTEM AND CHANNEL MODEL

A. CCRN and Channel Model

Let us consider a CCRN model as shown in Fig. 1 in which the SU-Tx communicates with a SU-Rx through the help of a single DF SR. We assume that the SU-Tx, SU- Rx, primary transmitter (PU-Tx), and primary receiver (PU- Rx) are equipped with a single antenna while the SR has N antennas. To enhance the spectrum utilization, the SUs simultaneously access the licensed frequency band of the PU given that their communication do not cause harmful interference to the PU.

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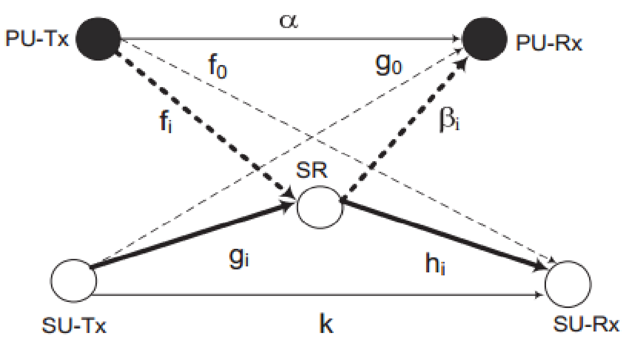

Fig. 1. System model of a cognitive cooperative radio network in which the SR is equipped with multiple antennas

For mathematical model, the channel gains from the SU-Tx to the antenna branch *i*-th of the SR and from the antenna branch *i*-th of the SR to the SU-Rx as g_i and h_i, $i = 1, 2. . . , N$, respectively. The channel gains of SU-Tx→SU-Rx and PU-Tx→PU-Rx links are symbolized by α and k, respectively. Furthermore, the channel gains of the SU-Tx→PU-Rx, SR→PU-Rx, Pu-Tx→SR, and PU-Tx→SU-Rx interference links are denoted by g_0, β_i, f_i, and f_0, respectively, $i\in\{1,2,\ldots,N\}$. We assume that channels are subject to Rayleigh fading, hence channel gains are exponential distributed random variables (RVs). Accordingly, the channel mean gains of k, g_0, f_0, g_i, f_i, β_i, and α, are expressed, respectively, by Ω_k, Ω_{go}, Ω_{fo}, Ω_g, Ω_f, Ω_β, and Ω_α. Communication in the secondary network is scheduled as follows. In the first time slot, the SU-Tx broadcasts its signals to SR and the SU-Rx. Accordingly, the signal-to-interference- plus-noise ratio (SINR) received at the antenna branch *i*-th of the SR can be formulated as

$$\gamma SR_i = \frac{P_S g_i}{P_P f_i + N_0} \tag{1}$$

where P_P , P_S , and N_0 are PU average transmit power, SU-Tx instantaneous transmit power, and noise power, respectively. It is noted that the SR uses selection combining technique to process the signal, then the SINR at the SR is expressed by

$$\gamma_1 = \max_{i\in\{1,2,\ldots N\}}\{\gamma SR_i\} \tag{2}$$

Also, the SINR received at the SU-Rx in the direct link is defined as

$$\gamma_0 = \frac{P_S k}{P_P f_0 + N_0} \tag{3}$$

In order to not degrade the outage probability of the PU, the SU-Tx should have an adaptive transmit power policy to satisfy the outage constraint given by the PU-Rx. Thus, the SU-Tx peak transmit power can be expressed as follows:

$$P_{out}^{p^1} = \Pr\left\{\frac{P_P\alpha}{P_S g_0 + N_0} < \theta\right\} \le \varepsilon \tag{4}$$

$$P_S \le P_{pk}^{(1)} \tag{5}$$

Where θ and ε denote the outage threshold and outage constraint of the PU-Rx, respectively, and $P_{pk}^{(1)}$ stands for the SU-Tx peak transmit power. In the second time slot, *i*-th antenna at the relay is selected to transmit the signal to the SU-Rx, the SINR at the SU-Rx can be expressed as

$$\gamma RD_i = \frac{P_R h_i}{P_P f_0 + N_0} \tag{6}$$

Since, the SR have N antennas and one of N antennas at the relay is selected to maximal the received signal at the SU-Rx. Accordingly, the SINR at the SU-Rx can be presented as

$$\gamma_2 = \max_{i\in\{1,2,\ldots,N\}}\{\gamma RD_i\} \tag{7}$$

where P_R is the instantaneous transmit power of the SR. Similar to the first time slot, the SR must control its transmit power to ensure the outage constraint of the PU and the peak transmit power of the SR, i.e.,

$$P_{out}^{p^2} = \Pr\left\{\frac{P_P\alpha}{P_R\beta_i + N_0} < \theta\right\} \le \varepsilon \tag{8}$$

$$P_R \le P_{pk}^{(2)} \tag{9}$$

where $P_{pk}^{(2)}$ denotes the SR peak transmit power.

B. End-to-end SINR

To prove the efficiency of the SC/TAS technique, we compare it with the conventional SC technique.

1) Conventional SC technique: The conventional SC technique can be expressed as follows:

$$\gamma SC = \max\left\{\gamma_0, \max\left\{\min_{i\in\{1,2,\ldots,N\}}\{\gamma SR_i, \gamma SD_i\}\right\}\right\} \tag{10}$$

2) SC/TAS technique: In order to enhance the system performance, the SR will process the signal as follows:

$$\gamma SC/TAS = \max\{\gamma_0, \min\{\gamma_1, \gamma_2\}\} \tag{11}$$

In other words, the SU-Rx will compare the received signal via the relay to the direct link and then select the maximal one.

III. PERFORMANCE ANALYSIS

To obtain the power allocation policy for the SU-Tx and the SR, let us recall the *Property 1* shown in [18] as follows:

Property 1: Assume that X and Y are exponentially distributed RVs with mean Ω_x and Ω_y , respectively. The cumulative distribution function (CDF) of an RV $Z = aX/(bY + c)$ with $a,b,c > 0$ is formulated as

$$F_Z(a,b,c,\Omega_x,\Omega_y,z) = 1 - a\Omega_x \frac{\exp(-\frac{zc}{a\Omega_x})}{zb\Omega_y + a\Omega_x} \tag{12}$$

A. Power Allocation Policy for the SU-Tx

Using (12) for the term of outage probability, $P_{out}^{p^1}$, expressed in (4), yields

$$\begin{aligned} P_{out}^{p^1} &= F_Z(P_P, P_S, N_0, \Omega_\alpha, \Omega_{g0}, \theta) \\ &= 1 - \frac{P_P\Omega_\alpha}{\theta P_S\Omega_{g0} + P_P\Omega_\alpha}\exp(-\frac{N_0\theta}{P_P\Omega_\alpha}) \end{aligned} \tag{13}$$

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In addition, substituting (13) into (4), the maximal transmit power of SU-Tx under the outage constraint of the PU is obtained as

$$P_S = \frac{P_P\Omega_\alpha}{\theta\Omega_{g0}}\Gamma \qquad (14)$$

Where $\Gamma = \max\left\{0, \frac{1}{1-\varepsilon}\exp\left(-\frac{\theta N_0}{P_P\Omega_\alpha}\right)-1\right\}$. Finally, an adaptive power allocation policy for the SU-Tx is established by combining (14) with (5) as

$$\mathcal{P}_S = \min\left\{P_{pk}^{(1)}, \frac{P_P\Omega_\alpha}{\theta\Omega_{g0}}\Gamma\right\} \qquad (15)$$

B. Power Allocation Policy of the SR

Similarly, in the second time slot, the SR selects one of the antennas to transmit the signals to the SU-Rx. It is noted that the selected antenna must keep the interference at the PU-Rx below a predefined threshold and the received SINR of the SU-Rx is maximal. Here, we note that the SR must control its transmit power to satisfy its peak transmit power and the outage constraint of the primary network. By using the same derivation as in Section III-A, the outage probability of the PU under the effect of interference from the transmit antenna *i*-th is written as

$$P_{out}^{p^2} = F_Z(P_P, P_{R_i}, N_0, \Omega_\alpha, \Omega_\beta, \theta) \qquad (16)$$

and the adaptive transmit power allocation policy for the SRi is given by

$$\mathcal{P}_{\mathcal{R}i} = \min\left\{P_{pk}^{(2)}, \frac{P_P\Omega_\alpha}{\theta\Omega_\beta}\Gamma\right\} \qquad (17)$$

It should be noted that the channel mean powers of the SR$_i$ $\longrightarrow$ PU-Rx links, Ω_β, are identical. Therefore, $\mathcal{P}_{\mathcal{R}i}$, given in (17) are identical and they can be writen as $\mathcal{P}_{\mathcal{R}} = \mathcal{P}_{\mathcal{R}i}$, $i \in \{1, 2, \ldots, N\}$

C. Outage Probability

Outage probability is defined as the probability of SINR is smaller than a predefined threshold. Accordingly, the outage probabilities of the SC and SC/TAS techniques are presented, respectively, as follows:

$$\mathcal{O}_{SC} = \Pr\{\gamma SC < \gamma th\} \qquad (18)$$

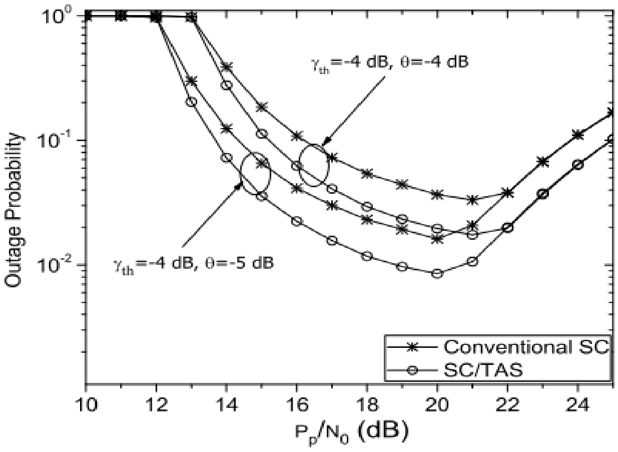
$$\mathcal{O}_{SC/TAS} = \Pr\{\gamma SC/TAS < \gamma th\} \qquad (19)$$

where γth is outage threshold of the secondary network.

IV. NUMERICAL RESULTS

In this section, simulation results are provided to investigate the performance of the considered schemes. Specifically, the system parameters are set as follows: PU outage constraint ε =1%, noise power N_0=5.10^{-3}Watt. Peak signal-to-noise ratio (SNR) $\gamma_{pk}^{(1)} = \frac{P_{pk}^{(1)}}{N_0} = 15dB$, and $\gamma_{pk}^{(2)} = \frac{P_{pk}^{(2)}}{N_0} = 15dB$.

In Fig. 2, the outage probability is plotted as the function of the SNR, P_P/N_0,for different values of outage threshold. It is easy to see that the outage probability of the SC/TAS scheme outperforms the one of the SC scheme. Also, we can observe that the outage probability firstly decreases to an optimal point and then increase thereafter. This can be explained by the fact that the SU-Tx and SR can adjust their transmitted power according to the change of the PU-Tx. However, as the PU-Tx transmitted power increase further, the SUs can not increase further due to the peak transmit power constraint. At this point the PU-Tx becomes a strong



interference source which degrades the PU performance.

Fig. 2. Outage probability of SC and SC/TAS techniques where channel mean power gains are set as: $\Omega_g = \Omega_h = \Omega_k = 1$, $\Omega_\beta = \Omega_f = 0.2$, $\Omega_{g0} = \Omega_{f0} = 0.2$, and $\Omega_\alpha = 2$.

Number of antennas at the SR is set to N=5; In Fig. 3, the outage probability is plotted with different values of channel mean power gains of interference links. We can see that the outage probability is improved significantly as the channel mean power gains of interference links degrade. This can be explained by the fact that the channel mean power gains of interference links are small, i.e., the mutual interfer- ence between the SU and PU is very small. Accordingly, the outage threshold of the PU is still satisfied as the SU and SR increase their transmitted power, and hence the outage probability of the SU is improved. In Fig. 4, we plot the outage probability with different number of antennas, we can see that as the number of antennas increase the outage probability degrades significantly. This can be explained as follows. As the number of antennas increase, the probability that the antenna at the SR receives and transmits the signals without cause harmful interference to the PU-Rx increase, accordingly, the outage probability is improved.

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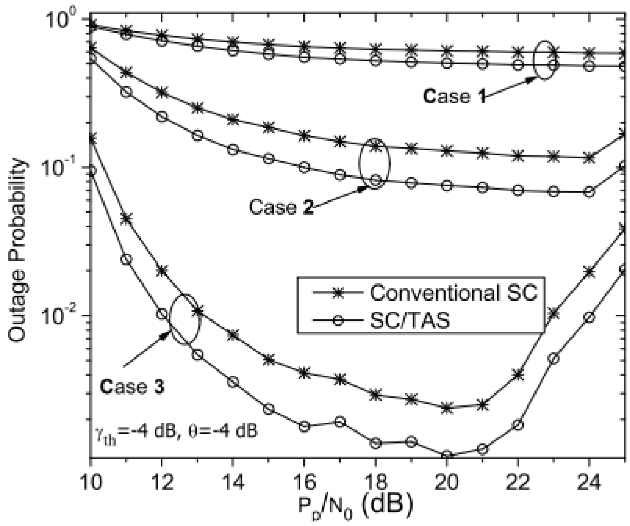

Fig. 3. Outage probability with identical channel mean gains of commu- nication links $\Omega_g = \Omega_h = \Omega_k = \Omega_\alpha = 5$, and Case 1: $\Omega_\beta = \Omega_f = \Omega_{g0} = \Omega_{f0} = 2$; Case 2: $\Omega_\beta = \Omega_f = \Omega_{g0} = \Omega_{f0} = 1$; Case 3: $\Omega_\beta = \Omega_f = \Omega_{g0} = \Omega_{f0} = 0.5$

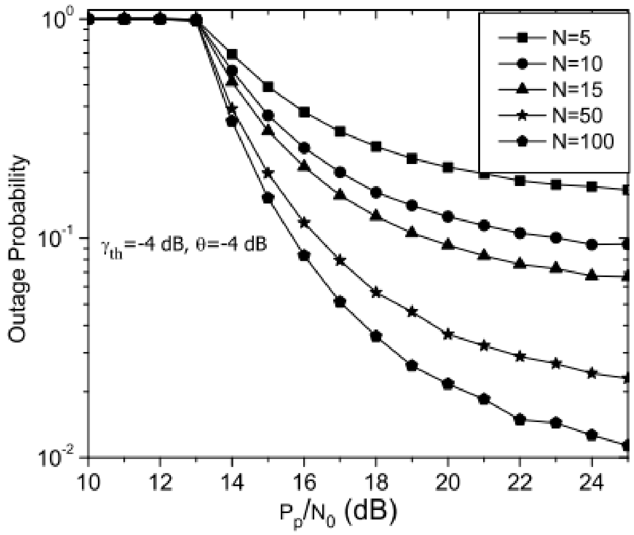

Fig. 4. Outage probability with different number of antennas, N = 5, 10, 15, 50, 100 in which channel mean powers are set as $\Omega_g = \Omega_h = \Omega_k = \Omega_\alpha = 2$, $\Omega_\beta = \Omega_f = \Omega_{g0} = \Omega_{f0} = 0.5$

V. CONCLUSIONS

In this paper, we have studied the performance DF relaying schemes in CCRN in terms of outage probability. Subject to the outage constraint of the PU and the peak transmit power of the SU-Tx and SR, adaptive power allocation policies for the SU-Tx and SR have been investigated. Using adaptive power allocation policies for the SU-Tx and SR, simulations for the outage probability of the SC/TAS and the SC scheme have been obtained. Simulation results have shown facts that the performance of the SC/TAS scheme is better than the one of the SC scheme and the massive antennas at the SR can improve the system performance significantly. Last but not least, the transmitted power of the PU-Tx and the channel mean power gains of the interference links are important parameters which can be utilized to improve the system performance.

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