Performance Analysis of Cognitive Cooperative Communication System Based on Optimal Relay Selection Scheme

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***Abstract*—**Since the electromagnetic spectrum resource is becoming more and more scarce, a new communication scheme is proposed for the cognitive cooperative system. In this scheme, to avoid harmful interference with primary users, the transmit power of the secondary source and relays are limited with respect to the interference power constraints at primary users and coefficients of fading channels. Moreover, the optimal relay selection scheme is exploited to further enhance the system performance. Based on the closed-form distribution function of the end-to-end signal-to-noise ratio obtained herein, the outage probability of the system under study is analytically investigated. Then we compare the performance in terms of outage probability of the use of fixed transmit power (FTP) and adaptive transmit power (ATP). Our results show that system performance is dominated by the quantity of the relays and the power constraints. In addition, the outage performance of the system with ATP is better than the system with FTP, especially at the large SNR district. However, the use of FTP requires less signaling overhead than the use of ATP. Finally, all analytical results are exhibited and corroborated by simulation results.

***Index Terms*—**Cognitive radio, decode-and-forward, outage probability, relay selection

I. Introduction

With the rapid development of the wireless communication, the available spectrum is becoming overcrowded. Thus, improving spectrum usage and transmission efficiency has become a significant topic both in academia and industry. To overcome this problem, cognitive radio is widely applied. Specifically, it offers tremendous potential to improve the spectrum usage by allowing secondary users to access the spectrum bands licensed to primary users while adhering to the interference limitations of the primary users [1]. In general, the interference limitations can be defined by means of the peak interference power, average interference power or both [2].

On the other hand, cooperative communications have also been a popular topic owing to their ability of exploiting spatial diversity. It is generally known that there are two traditional cooperative protocols, namely, amplify-and-forward (AF) and decode-and-forward (DF) respectively [3]. The amplify-and-forward strategy allows the relay stations to amplify the received signal from the source node and to forward it to the destination station. The decode-and-forward strategy allows the relay stations to overhear transmissions from the source, decode them and in case of correct decoding, forward them to the destination. Whenever unrecoverable errors reside in the overheard transmission, the relays cannot contribute to the cooperative transmission. Therefore the consecutive hops in DF relaying systems are separated by the decoding operation and system performance is dominated by the worst hop.

For AF relay network, in [4], two relay-selection strategies including partial relay selection and opportunistic relay selection were proposed and exploited to further enhance the system performance. Moreover, the closed-form expressions for the effective capacity of the channel in Rayleigh block-fading environment under peak or average interference power constraints were derived.

For DF relay network, the finite signal-to-noise ratio (SNR) diversity-multiplexing trade-off of point-to-point wireless channels assisted by multiple relays was investigated in [5]. In [6], the authors developed a high-performance cooperative maximum-ratio-combining (C-MRC) demodulator and proved that full diversity gains can be achieved with C-MRC in general cooperative links. Different relay selection strategies have been considered in [7] and [8]. In [7], a relay selection criterion from the information theoretic aspect was proposed, in which the relays were allowed to cooperate if their source-relay channel coefficient magnitudes exceeded a threshold. The location-based relaying node selection schemes were used in [8]. Nevertheless, it is found that the primary users in DF relay network have not been considered in [5]-[8]. Although the closed-form expressions of outage probability were obtained for a cognitive communication system in [9]-[12], the authors didn't consider relay selection scheme the existence of direct channel in their systems. In [13], authors have proposed to select the relay

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with the largest signal-to-noise ratio (SNR) in relay-destination link under the constraint of satisfying a required primary outage probability, but it neglected the correlation among the channel gains.

However, in all of these papers, the secondary nodes are assumed to adapt their transmission power (ATP) in order to always satisfy the interference constraint. Recently, some efforts have focused on the use of secondary transmitter nodes using fixed transmit power (FTP). This is not unrealistic, and there are many wireless devices, especially the non-cellular ones, which have a fixed transmission power, for example, wireless routers and other Wi-Fi devices. Furthermore, transmit power adaptation comes with increased hardware complexity, processing power and cost, as mentioned in various papers dealing with transmit power control and adaptation algorithms [14]. There may be situations where the network's nodes could not be equipped with these features because of hardware, cost or size constraints. For example, it may be a sensor node to measure some data and transmit it to a certain collection point and its processing power is limited by its battery life. In [15] and [16], several relaying schemes were investigated where secondary transmitters (source and relay) use their maximum available power when the primary interference constraint is verified and remain silent otherwise. The authors in [15] and [16] only considered single primary user close to the secondary system. Therefore, this is the gap which this paper aspires to fill.

The main contributions of this paper are described as follows. Firstly, unlike the previous research about relay selection in conventional networks, we investigate the performance of relay selection for a DF relay system with a source-destination direct link in cognitive radio networks, and propose the optimal relay selection schemes with ATP and FTP respectively. Secondly, the exact closed-form expressions for the outage probability of both schemes are derived, and the asymptotic expression at high SNR with ATP is also presented. Moreover, we compare the performance of the two power schemes. Finally, analytical results show that the system performance is dominated by the quantity of the relays and the power constraints. And our comparison study shows that the outage performance of the system with ATP is better than the system with FTP, especially at the large SNR district. However, the use of FTP requires less signaling overhead than the use of ATP.

II. System Model

Consider a dual-hop cognitive cooperative communication system in DF strategy as shown in Fig. 1, where a secondary source S and a destination D are located close to the two primary users PU_1 and PU_2 respectively. The secondary source S sends signals to the destination D with the help of multiple intermediate relaying nodes $\mathrm{R}_1, \mathrm{R}_2, \cdots, \mathrm{R}_N$. Furthermore, the direct link between S and D is also available. The transmit powers of the secondary source and relaying nodes are limited by PU_1 and PU_2 respectively.

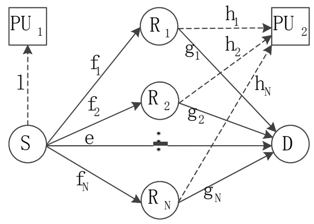

Fig. 1. System model of cognitive cooperative communication with N DF relays.

We assume that all the nodes operate in half-duplex mode, and the end-to-end information transmission occupies two time slots. In the first time slot, the source S with transmission power P_S broadcasts its signal. This signal is received by the destination, all the relays and one primary user with channel gains e, f_i, l. Accordingly, the instantaneous SNRs at the ith relay R_i, $i = 1, 2, \cdots, N$, and the destination D are given by

$$\gamma_{\mathrm{f}_i} = \frac{P_{\mathrm{S}} |f_i|^2}{\sigma_i^2} \tag{1}$$

and

$$\gamma_{\mathrm{e}} = \frac{P_{\mathrm{S}} |e|^2}{\sigma_{\mathrm{e}}^2} \tag{2}$$

where σ_i^2 and σ_{e}^2 represent the variances of additive white Gaussian noise (AWGN) at relay R_i and D with zero mean. For ease of notation and without loss of generality, it is assumed throughout the rest of the paper that the AWGNs at all nodes have the same variance σ^2.

With this assumption, secondary users are required to have an estimate of the secondary to primary interference channel. Suppose that l and h_i denote the channel coefficients of the links $\mathrm{S} \rightarrow \mathrm{PU}_1$ and $\mathrm{R}_i \rightarrow \mathrm{PU}_2$, in addition, the source and each relay is aware of these channel. Suppose that g_i represents the channel gain of the link $\mathrm{R}_i \rightarrow \mathrm{D}$. Then the instantaneous SNRs of the links $\mathrm{R}_i \rightarrow \mathrm{D}$, $\mathrm{R}_i \rightarrow \mathrm{D}$, and $\mathrm{R}_i \rightarrow \mathrm{PU}_2$ are denoted by γ_{g_i}, γ_{l}, and γ_{h_i} respectively.

To simplify the analysis and reach some intelligible results, we consider that the relays are present in the form of a cluster and are roughly at the same distance from the secondary source and destination, making the average strengths of the interfering channels and the secondary SNR of each relay link to be the same. Hence we assume that all the coefficients f_i are identically distributed, all the coefficients g_i are identically distributed, and all the coefficients h_i are identically distributed, furthermore, all the links in this system are subject to independent Rayleigh fading. Therefore, γ_{f_i}, γ_{g_i}, γ_{h_i}, γ_{l}, γ_{e} follow independent exponential distribution with mean $\bar{\gamma}_{f_i} = P_S\Omega_f / \sigma^2$, $\bar{\gamma}_{g_i} = P_{R_i}\Omega_g / \sigma^2$, $\bar{\gamma}_{h_i} = P_{R_i}\Omega_h / \sigma^2$, $\bar{\gamma}_l = P_S\Omega_l / \sigma^2$, $\bar{\gamma}_e = P_S\Omega_e / \sigma^2$, where $\Omega_f = \mathbb{E}[|f_i|^2]$, $\Omega_g = \mathbb{E}[|g_i|^2]$, $\Omega_h = \mathbb{E}[|h_i|^2]$, $\Omega_l = \mathbb{E}[|l|^2]$, $\Omega_e = \mathbb{E}[|e|^2]$, and $\mathbb{E}[\cdot]$ denotes the expectation operator.

Relay selection takes place in the second time slot and the best one is chosen on the basis of the criteria explained in the next section. Assume that the *b*th relay R_b is selected by a certain criterion. The selection process could be implemented through a dedicated centralized node that has the global channel state information (CSI) or in a distributed fashion as described in [17]. Depending upon the way a scheme is implemented, CSI requirements at different network nodes will vary. The chosen best relay R_b then forwards its signals with power P_{R_b} to D in DF mode, and then the instantaneous SNRs γ_{g_b} can be given by

$$\gamma_{g_b} = \frac{P_{R_b}|g_b|^2}{\sigma^2} \tag{3}$$

In underlay cognitive radio network, the interference level at primary user caused by the secondary transmitters (source and relays) must be below an interference threshold noted, thus the constraint condition can be derived as

$$\mathcal{I}_S \triangleq P_S|l|^2 \le Q_1 \tag{4}$$

and

$$\mathcal{I}_{R_i} \triangleq P_{R_i}|h_i|^2 \le Q_2 \tag{5}$$

where Q_1 and Q_2 are the tolerable interference power at PU_1 and PU_2 respectively. For ease of notation and without loss of generality, let all relays have the same transmit power, namely, $P_{R_i} = P_R$. Then, Two power allocation schemes can be used: adaptive transmit power and fixed transmit power.

III. Criteria for Relay Selection

The best relay selection in underlay cognitive networks is entirely different from the traditional non-cognitive cooperative networks where, in most cases, the best relay is selected on the basis of maximum end-to-end SNR. Contrarily, in cognitive networks, a relay that could maintain the maximum secondary SNR may also create more interference to the primary user in the absence of transmit power adaptation. Hence, the relay selection process must respect the end-to-end SNR as well as the interference constraint imposed by the primary system. In the following, we present the relaying schemes using FTP and ATP respectively.

A. Relay Selection with ATP

In this scheme, in order to maximize the system performance while respecting the interference constraint, each transmitter adjusts its power before each transmission as follows:

$$P_S^A = \min\left\{\frac{Q_1}{|l|^2}, P\right\} \tag{6}$$

and

$$P_R^A = \min\left\{\frac{Q_2}{|h_i|^2}, P\right\} \tag{7}$$

where P denotes the maximum transmit power of S and R_i. To select a relay, the decoding set of relays $\mathbf{\Psi}$ is first formed, i.e., the relays that have correctly decoded the received signal. The instantaneous mutual information of the link $S \to R_b$ is given by $I_{f_b} = 0.5\log_2(1+\gamma_{f_b})$, and the decoding set can be defined as

$$\mathbf{\Psi} \triangleq \left\{R_i \middle| \gamma_{f_i} \geqslant \gamma_{th}\right\} \tag{8}$$

where $\gamma_{th} = 2^{2r_0} - 1$, and r_0 is a given threshold rate. There exists a non-zero probability that none of the relays satisfies constraint (8), and the destination only receives the direct signal from the source. If the decoding set $\mathbf{\Psi}$ is not null, then, the selected relay denoted by R_b^A is the one that maximizes the SNR of the relay-destination link, namely, $R_b^A = \arg\max_{R_b \in \Psi} \gamma_{g_i}$.

B. Relay Selection with FTP

In this scheme, the powers of source and relays can be denoted by P_S^F and P_R^F, and the selected relay must respect the three following constraints:

- Interference constraint: the level of the interference caused by the selected relay should be below the threshold allowed by the primary user.
- Decoding constraint: the selected relay should correctly decode the secondary signal.
- Finally, the selected relay should maximize the SNR of the relay-destination link.

Thus, to select a relay, we first determine the set $\mathbf{C}$ consisting of the relays satisfying the interference constraint. The set $\mathbf{C}$ can be defined as

$$\mathbf{C} \triangleq \left\{R_i, 1 \leqslant i \leqslant N \middle| P_{R_i}^F |h_i|^2 \le Q_2\right\} \tag{9}$$

Next determine the decode set $\mathbf{\Psi}$ from the set $\mathbf{C}$. If the decoding set $\mathbf{\Psi}$ is null, the signals will be also transmitted by the direct link $S \to D$. Finally, the selected relay denoted by R_b^T is the one that maximizes the SNR of the relay-destination link, hence, $R_b^T = \arg\max_{R_b \in \Psi} \gamma_{g_i}$.

C. Signaling Overhead Structure Comparison

We compare the signaling overhead structure complexity of the two schemes, namely, ATP and FTP, as shown in the Fig. 2 and Fig. 3 [15]. Let S be the dedicated centralized node that is responsible for collecting, sensing the CSI and selecting the relays.

As shown in Fig. 2, if the secondary source and relay nodes use FTP, the transmission process will start only when S senses $\mathcal{I}_{\mathrm{S}} \le Q_1$, and then each relay compares $P_{\mathrm{R}_i}^{\mathrm{F}} |h_i|^2$ with Q_2. If R_i satisfies $\mathcal{I}_{\mathrm{R}_i} \le Q_2$, then it sends its identity and the value of g_i to S. S then collects the identities of the relays meeting the interference constraint and since it is assumed to have a prior knowledge about the values of $P_{\mathrm{R}_i}^{\mathrm{F}}$, $i = 1, 2, N$, it can select the best relay.

Relay ID	CSI g_i

Fig. 2. Signaling overhead structure of FTP.

Relay ID	CSI g_i	Power$P_{\mathrm{R}_i}^{\mathrm{A}}$

Fig. 3. Signaling overhead structure of ATP.

As shown in Fig. 3, if the nodes use ATP, each relay adjusts its powers to satisfy the interference constraint $\mathcal{I}_{\mathrm{R}_i} \le Q_2$, and sends its identity, the value of g_i and its instantaneous power $P_{\mathrm{R}_i}^{\mathrm{A}}$ to S. In order to select the best relays and meet the interference demand, the relays with ATP have to change their transmit power continuously, so it has to send the value of its instantaneous transmit power $P_{\mathrm{R}_i}^{\mathrm{A}}$ to the source S, and it will consume more resources to carry the signaling information. Obviously, when the number of relays increases, the signaling amount required to transmit this information becomes huge.

IV. Outage Probability Analysis

In this section, we derive the closed-form expression of the outage probability of the relay selection scheme with ATP and FTP respectively. No matter which power scheme is adopted, the end-to-end instantaneous SNRs of the two schemes are similar and can be given by

$$\gamma^{\mathrm{opt}} = \begin{cases} \gamma_{\mathrm{e}}, & |\boldsymbol{\Psi}| = 0 \\ \max\{\max\limits_{i \in \Psi} \gamma_{\mathrm{g}_i}, \gamma_{\mathrm{e}}\}, & |\boldsymbol{\Psi}| \neq 0 \end{cases} \tag{10}$$

where $|\boldsymbol{\Psi}|$ denotes the cardinality of the decoding set $\boldsymbol{\Psi}$.

A. Outage Probability of ATP

Using the law of total probability, and from (10), we can derive the outage probability as follow:

$$\begin{aligned} P_{\mathrm{out}}^{\mathrm{ATP}}(\gamma_{\mathrm{th}}) &= \Pr\{\gamma^{\mathrm{opt}} \le \gamma_{\mathrm{th}}\} \\ &= \Pr\{|\boldsymbol{\Psi}| = 0\} \Pr\{\gamma_{\mathrm{e}} \le \gamma_{\mathrm{th}}\} \\ &\quad + \sum_{K=1}^{N} \binom{N}{K} \Pr\{|\boldsymbol{\Psi}| = K\} \\ &\quad \times \Pr\left\{\max\left(\max_{1 \le i \le K} \gamma_{\mathrm{g}_i}, \gamma_{\mathrm{e}}\right) \le \gamma_{\mathrm{th}}\right\} \end{aligned} \tag{11}$$

Suppose that there are K relay nodes in $\boldsymbol{\Psi}$ which can decode the signals received from S perfectly in the first slot. In order to establish the decoding set $\boldsymbol{\Psi}$, γ_{f_i} is needed. Substituting (6) into (1), we can find that all γ_{f_i} are correlated because there is always $|l|^2$ in every γ_{f_i}. To remove the correlation among all γ_{f_i}, we let $|l|^2 = x$, where x is a given constant, then all γ_{f_i} are independent. Therefore, we ought to calculate the conditional probability $P_{\mathrm{out}}\left(\gamma_{\mathrm{th}} \middle| |l|^2 = x\right)$, and then average the conditional probability for all x, For ease of notation, let $\varphi \triangleq |l|^2$, $\gamma_{\mathrm{g}} \triangleq \max\limits_{1 \leqslant i \leqslant K} \gamma_{\mathrm{g}_i}$. From (11), we can derive the conditional probability as follow:

$$\begin{aligned} P_{\mathrm{out}}(\gamma_{\mathrm{th}} | \varphi = x) &= \Pr\{\gamma^{\mathrm{opt}} \leqslant \gamma_{\mathrm{th}} | \varphi = x\} \\ &= \Pr\{|\boldsymbol{\Psi}| = 0 | \varphi = x\} \Pr\{\gamma_{\mathrm{e}} \leqslant \gamma_{\mathrm{th}} | \varphi = x\} \\ &\quad + \sum_{K=1}^{N} \binom{N}{K} \Pr\{|\boldsymbol{\Psi}| = K | \varphi = x\} \\ &\quad \times \Pr\left\{\max\left(\max_{1 \le i \le K} \gamma_{\mathrm{g}_i}, \gamma_{\mathrm{e}}\right) \leqslant \gamma_{\mathrm{th}} | \varphi = x\right\} \end{aligned} \tag{12}$$

Next, each part of (12) will be calculated in the ensuing part consecutively.

1) Formulate $\Pr\{|\boldsymbol{\Psi}| = K | \varphi = x\}$: From (8), we can derive

$$\begin{aligned} \Pr\{|\boldsymbol{\Psi}| = K | \varphi = x\} &= \left[1 - F_{\gamma_{\mathrm{f}_i}}(\gamma_{\mathrm{th}} | \varphi = x)\right]^K \\ &\quad \times \left[F_{\gamma_{\mathrm{f}_i}}(\gamma_{\mathrm{th}} | \varphi = x)\right]^{N-K} \end{aligned} \tag{13}$$

where $F_{\gamma_{\mathrm{f}_i}}(\cdot)$ denotes the cumulative distribution function (CDF) of γ_{f_i}. So it is necessary that $F_{\gamma_{\mathrm{f}_i}}(\cdot)$ should be derived in order to obtain the outage probability. Using (1), (6) and some manipulations, we can obtain that

$$F_{\gamma_{\mathrm{h}_i}}(\gamma_{\mathrm{th}} | \varphi = x) = \begin{cases} 1 - \exp\left(-\dfrac{\sigma^2 \gamma_{\mathrm{th}}}{P\Omega_{\mathrm{f}}}\right), & x \leqslant \dfrac{Q_1}{P} \\ 1 - \exp\left(-\dfrac{\sigma^2 x \gamma_{\mathrm{th}}}{Q_1 \Omega_{\mathrm{f}}}\right), & x > \dfrac{Q_1}{P} \end{cases} \tag{14}$$

Letting $\rho_m \triangleq -\dfrac{\sigma^2 \gamma_{\mathrm{th}}}{P\Omega_m}$, $\theta_{nm} \triangleq -\dfrac{\sigma^2 \gamma_{\mathrm{th}}}{Q_n \Omega_m}$, where $n = 1, 2$ and $m = \mathrm{f}, \mathrm{g}, \mathrm{e}$, then substituting (14) into (13), we have

$$\Pr\{|\Psi| = K | \varphi = x\} = \begin{cases} \mathrm{e}^{K\rho_{\mathrm{f}}} \left(1 - \mathrm{e}^{\rho_{\mathrm{f}}}\right)^{N-K}, & x \leqslant \dfrac{Q_1}{P} \\ \mathrm{e}^{Kx\theta_{1\mathrm{f}}} \left(1 - \mathrm{e}^{x\theta_{1\mathrm{f}}}\right)^{N-K}, & x > \dfrac{Q_1}{P} \end{cases} \tag{15}$$

2) Formulate $\Pr\{\gamma_{\mathrm{e}} \leqslant \gamma_{\mathrm{th}} | \varphi = x\}$: Easily, using the similar approach as in (14), we can derive   as follows:

$$\Pr\{\gamma_{\mathrm{e}} \leqslant \gamma_{\mathrm{th}} | \varphi = x\} = \begin{cases} 1 - \mathrm{e}^{\rho_{\mathrm{e}}}, & x \leqslant \dfrac{Q_1}{P} \\ 1 - \mathrm{e}^{x\theta_{1\mathrm{e}}}, & x > \dfrac{Q_1}{P} \end{cases} \tag{16}$$

3) Formulate $\Pr\{\max(\gamma_{\rm g},\gamma_{\rm e}) \leqslant \gamma_{\rm th} | \varphi = x\}$: Clearly, from (2), (3), it is easy to notice that all $\gamma_{{\rm g}_i}$ and $\gamma_{\rm e}$ are independent of each other, so we can obtain

$$\begin{aligned}&\Pr\left\{\max\left(\gamma_{\rm g},\gamma_{\rm e}\right) \leqslant \gamma_{\rm th} | \varphi = x\right\} \\ &= F_{\gamma_{\rm g}}\left(\gamma_{\rm th}\right) F_{\gamma_{\rm e}}(\gamma_{\rm th} | \varphi = x)\end{aligned} \tag{17}$$

Obviously, in order to calculate this expression, $F_{\gamma_{\rm g}}\left(\gamma_{\rm th}\right)$ is needed. Because all $\gamma_{{\rm g}_i}$ are independent, $F_{\gamma_{\rm g}}\left(\gamma_{\rm th}\right)$ can be derived as

$$F_{\gamma_{\rm g}}\left(\gamma_{\rm th}\right) = \left\{1 - {\rm e}^{\rho_{\rm g}} + \left[1 + \frac{1}{\Omega_{\rm h}}\left(\theta_{2{\rm g}} - \frac{1}{\Omega_{\rm h}}\right)\right] {\rm e}^{\rho_{\rm g} - \frac{Q_2}{P\Omega_{\rm h}}}\right\}^K \tag{18}$$

Letting

$$\chi \triangleq \left\{1 - {\rm e}^{\rho_{\rm g}} + \left[1 + \frac{1}{\Omega_{\rm h}}\left(\theta_{2{\rm g}} - \frac{1}{\Omega_{\rm h}}\right)\right] {\rm e}^{\rho_{\rm g} - \frac{Q_2}{P\Omega_{\rm h}}}\right\}^K \tag{19}$$

and substituting (16) and (18) into (17), we can obtain

$$\begin{aligned}&\Pr\left\{\max\left(\gamma_{\rm g},\gamma_{\rm e}\right) \leqslant \gamma_{\rm th} | \varphi = x\right\} \\ &= \begin{cases}\chi\left(1 - {\rm e}^{\rho_{\rm e}}\right), & x \leqslant \dfrac{Q_1}{P} \\ \chi\left(1 - {\rm e}^{x\theta_{1{\rm e}}}\right), & x > \dfrac{Q_1}{P}\end{cases}\end{aligned} \tag{20}$$

4) Formulate outage probability: Substituting (15), (16), and (20) into (12), we can obtain the conditional probability. Then, manipulating the law of total probability, we can derive the closed-form expression of the outage probability for the optimal relay selection scheme with ATP as shown in (34). Let $P/\sigma^2 \to \infty$, the asymptotic expression at high SNR can be obtained as in (35).

B. Outage Probability of FTP

5) In this scheme, firstly, from (4) and (5), we quantify the interference from the source to one primary user in the first time slot and from each relay to another primary user in the second time slot, respectively. If $\mathcal{I}_{\rm S} > Q_1$, the transmission process described previously could not work, in this case, the system would not restart until it satisfies the interference limit and qualifies for the transmission. Therefore, we can derive the outage probability as follow:

$$\begin{aligned}P_{\rm out}^{\rm FTP} = \Pr\left\{\mathcal{I}_{\rm S} > Q_1\right\} + \Pr\left\{\mathcal{I}_{\rm S} \le Q_1\right\} \times \\ \Pr\left\{\gamma^{\rm opt} \le \gamma_{\rm th} | \mathcal{I}_{\rm S} \le Q_1\right\}\end{aligned} \tag{21}$$

Next, we derive each term of (21).

1) Formulate $\Pr\left\{\mathcal{I}_{\rm S} \le Q_1\right\}$: The channel coefficient $|l|^2$ subjects to exponential distribution, and from (4), we have

$$\Pr\left\{P_{\rm S}^{\rm F} |l|^2 \le Q_1\right\} = 1 - \exp\left(-\frac{Q_1}{P_{\rm S}^{\rm F}\Omega_l}\right) \tag{22}$$

2) Formulate $\Pr\left\{\gamma^{\rm opt} \le \gamma_{\rm th} | \mathcal{I}_{\rm S} \le Q_1\right\}$: From (4) and (10), we can find that $\gamma^{\rm opt}$ and $\mathcal{I}_{\rm S}$ are independent, we have

$$\Pr\left\{\gamma^{\rm opt} \le \gamma_{\rm th} | \mathcal{I}_{\rm S} \le Q_1\right\} = \Pr\left\{\gamma^{\rm opt} \le \gamma_{\rm th}\right\} \tag{23}$$

after some manipulations

$$\begin{aligned}\Pr\left\{\gamma^{\rm opt} \le \gamma_{\rm th}\right\} = \Pr\left\{|\mathbf{\Psi}| = 0\right\} \Pr\left\{\gamma_{\rm e} \le \gamma_{\rm th}\right\} + \\ \Pr\left\{|\mathbf{\Psi}| \ne 0\right\} \Pr\left\{\max\left(\gamma_{\rm g},\gamma_{\rm e}\right) \le \gamma_{\rm th}\right\}\end{aligned} \tag{24}$$

In this scheme, in order to derive the cardinality of $\mathbf{\Psi}$, two cases arise: the first case is $|\mathbf{C}| = 0$ and the second case is $|\mathbf{C}| \ne 0$. So, firstly, the relays not satisfying the interference threshold are excluded from the group, and then select the relay that maximizes the SNR. We first determine the set $\mathbf{C}$, then the subset $\mathbf{\Psi}$, $\mathbf{\Psi} \subset \mathbf{C}$, therefore we have

$$\Pr\left\{|\mathbf{\Psi}| = 0\right\} = \Pr\left\{|\mathbf{C}| = 0\right\} + \Pr\left\{|\mathbf{C}| \ne 0, |\mathbf{\Psi}| = 0\right\} \tag{25}$$

and

$$\Pr\left\{|\mathbf{\Psi}| \ne 0\right\} = \sum_{k=1}^{N}\sum_{j=1}^{k} \Pr\left\{|\mathbf{\Psi}| = j \,\big|\, |\mathbf{C}| = k\right\} \tag{26}$$

From (9), we can derive

$$\Pr\left\{|\mathbf{C}| = 0\right\} = \prod_{i=1}^{N} \Pr\left\{|h_i|^2 > Q_2\right\} = \exp\left(-\frac{NQ_2}{P_{{\rm R}_i}^{\rm F}\Omega_{\rm h}}\right) \tag{27}$$

and

$$\Pr\left\{|\mathbf{\Psi}| = j \,\big|\, |\mathbf{C}| = k\right\} = \binom{k}{j}\left[1 - F_{\gamma_{{\rm f}_i}}\left(\gamma_{\rm th}\right)\right]^j \left[F_{\gamma_{{\rm f}_i}}\left(\gamma_{\rm th}\right)\right]^{k-j} \tag{28}$$

where $j \le k, k \ne 0$, $F_{\gamma_{{\rm f}_i}}\left(\gamma_{\rm th}\right)$ denotes the CDF of $\gamma_{{\rm f}_i}$. From (1), we have

$$F_{\gamma_{{\rm f}_i}}\left(\gamma_{\rm th}\right) = 1 - \exp\left(-\frac{\sigma^2\gamma_{\rm th}}{\Omega_{\rm f} P_{\rm S}}\right) \tag{29}$$

Then from (25)-(29), and after some manipulations, we can obtain

$$\begin{aligned}\Pr\left\{|\mathbf{\Psi}| = 0\right\} = {\rm e}^{NI_{\rm h2}} + \\ \sum_{k=1}^{N}\binom{N}{k}\left(1 - {\rm e}^{I_{\rm h2}}\right)^k {\rm e}^{(N-k)I_{\rm h2}}\left(1 - {\rm e}^{\tau_{\rm f}}\right)^k\end{aligned} \tag{30}$$

$$\begin{aligned}&\Pr\left\{|\mathbf{\Psi}| = 0\right\} = \\ &\sum_{k=1}^{N}\sum_{j=1}^{k}\binom{N}{k}\binom{k}{j}{\rm e}^{(N-k)I_{\rm h2}}{\rm e}^{j\tau_{\rm f}}\left(1 - {\rm e}^{I_{\rm h2}}\right)^k\left(1 - {\rm e}^{j\tau_{\rm f}}\right)^{k-j}\end{aligned} \tag{31}$$

$$\Pr\left\{\gamma_{\rm e} \le \gamma_{\rm th}\right\} = \left(1 - {\rm e}^{\tau_{\rm e}}\right) \tag{32}$$

$$\Pr\left\{\max\left(\gamma_{\rm g},\gamma_{\rm e}\right) \le \gamma_{\rm th}\right\} = \left(1 - {\rm e}^{\tau_{\rm g}}\right)^j \left(1 - {\rm e}^{\tau_{\rm e}}\right) \tag{33}$$

where $I_{mn} = -Q_n / P^{\mathrm{F}}\Omega_m$, $\tau_m = -\gamma_{\mathrm{th}}/\bar{\gamma}_m$, and $n = 1,2$, $m = \mathrm{f,g,h,l,e}$. Substituting (30)-(33) and (22) into (21), we can obtain the outage probability of the relay selection with FTP scheme as shown in (36).

$$
\begin{aligned}
P_{\text{out-exact}}^{\text{ATP}}(\gamma_{th}) &= \left(1-\mathrm{e}^{\rho_{\mathrm{f}}}\right)^{N}\left(1-\mathrm{e}^{\rho_{\mathrm{e}}}\right)\left(1-\mathrm{e}^{-\frac{Q_1}{P\Omega_l}}\right) + \chi\sum_{K=1}^{N}\binom{N}{K}\mathrm{e}^{K\rho_{\mathrm{f}}}\left(1-\mathrm{e}^{\rho_{\mathrm{f}}}\right)^{N-K}\left(1-\mathrm{e}^{\rho_{\mathrm{e}}}\right)\left(1-\mathrm{e}^{-\frac{Q_1}{P\Omega_l}}\right) \\
&+\sum_{j=0}^{N}\binom{N}{j}(-1)^{j}\frac{1}{\Omega_l}\left[\left(\frac{1}{\Omega_l}-j\theta_{1\mathrm{f}}\right)^{-1}\mathrm{e}^{j\rho_{\mathrm{f}}-\frac{Q_1}{P\Omega_l}}-\left(\frac{1}{\Omega_l}-\theta_{1\mathrm{e}}-j\theta_{1\mathrm{f}}\right)^{-1}\mathrm{e}^{\rho_{\mathrm{e}}+j\rho_{\mathrm{f}}-\frac{Q_1}{P\Omega_l}}\right]+\frac{\chi}{\Omega_l}\sum_{K=1}^{N}\sum_{j=0}^{N-K}(-1)^{j} \\
&\times\binom{N}{K}\binom{N-K}{j}\left[\left(\frac{1}{\Omega_{\mathrm{h}}}-(K+j)\theta_{1\mathrm{f}}\right)^{-1}\mathrm{e}^{(K+j)\rho_{\mathrm{f}}-\frac{Q_1}{P\Omega_l}}-\left(\frac{1}{\Omega_l}-(K+j)\theta_{1\mathrm{f}}-\theta_{1\mathrm{e}}\right)^{-1}\mathrm{e}^{(K+j)\rho_{\mathrm{f}}+\rho_{\mathrm{e}}-\frac{Q_1}{P\Omega_l}}\right]
\end{aligned} \tag{34}
$$

$$
\begin{aligned}
P_{\text{out-asym}}^{\text{ATP}}(\gamma_{th}) &= \sum_{j=0}^{N}\binom{N}{j}(-1)^{j}\frac{1}{\Omega_l}\left[\left(\frac{1}{\Omega_l}-j\theta_{1\mathrm{f}}\right)^{-1}-\left(\frac{1}{\Omega_l}-\theta_{1\mathrm{e}}-j\theta_{1\mathrm{f}}\right)^{-1}\right]+\frac{1}{\Omega_l}\sum_{K=1}^{N}\sum_{j=0}^{N-K}\binom{N}{K}\binom{N-K}{j} \\
&\times(-1)^{j}\left[1+\frac{1}{\Omega_{\mathrm{h}}}\left(\theta_{2\mathrm{g}}-\frac{1}{\Omega_{\mathrm{h}}}\right)^{-1}\right]^{K}\left[\left(-(K+j)\theta_{1\mathrm{f}}+\frac{1}{\Omega_l}\right)^{-1}-\left(-(K+j)\theta_{1\mathrm{f}}+\frac{1}{\Omega_l}-\theta_{1\mathrm{e}}\right)^{-1}\right]
\end{aligned} \tag{35}
$$

$$
\begin{aligned}
P_{\text{out-exact}}^{\text{FTP}}(\gamma_{th}) &= \mathrm{e}^{I_{\mathrm{l}1}}+\left(1-\mathrm{e}^{I_{\mathrm{l}1}}\right)\left(1-\mathrm{e}^{\tau_{\mathrm{e}}}\right)\left[\mathrm{e}^{NI_{\mathrm{h}2}}+\sum_{k=1}^{N}\binom{N}{k}\left(1-\mathrm{e}^{I_{\mathrm{h}2}}\right)^{k}\mathrm{e}^{(N-k)I_{\mathrm{h}2}}\left(1-\mathrm{e}^{\tau_{\mathrm{f}}}\right)^{k}\right] \\
&+\sum_{k=1}^{N}\sum_{j=1}^{k}\binom{N}{k}\binom{k}{j}\mathrm{e}^{(N-k)I_{\mathrm{h}2}}\mathrm{e}^{j\tau_{\mathrm{f}}}\left(1-\mathrm{e}^{I_{\mathrm{h}2}}\right)^{k}\left(1-\mathrm{e}^{j\tau_{\mathrm{f}}}\right)^{k-j}\left(1-\mathrm{e}^{\tau_{\mathrm{g}}}\right)^{j}\left(1-\mathrm{e}^{\tau_{\mathrm{e}}}\right)\left(1-\mathrm{e}^{I_{\mathrm{l}1}}\right)
\end{aligned} \tag{36}
$$

V. NUMERICAL RESULTS

In this section, computer simulations are performed to validate the analytical results. We assume that the distance between S and D is normalized to 1. The normalized distance from D to R_i is d_i. And the path loss exponent is 3. Assume that $d_1 = d_2 = \cdots = d_N = d$, then, $\Omega_{\mathrm{e}} = 1$, $\Omega_{\mathrm{f}} = d^{-3}$, $\Omega_{\mathrm{g}} = (1-d)^{-3}$. Generally, secondary sources and relay nodes are far away from primary users in order to avoid the interference, namely, $\Omega_{\mathrm{h}} < \Omega_{\mathrm{e}}$ and $\Omega_{\mathrm{l}} < \Omega_{\mathrm{e}}$, thus we assume $\Omega_{\mathrm{h}} = \Omega_{\mathrm{l}} = 0.5$. In addition, without loss of generality, we set $d = 0.6$, $r_0 = 2$ bps / Hz.

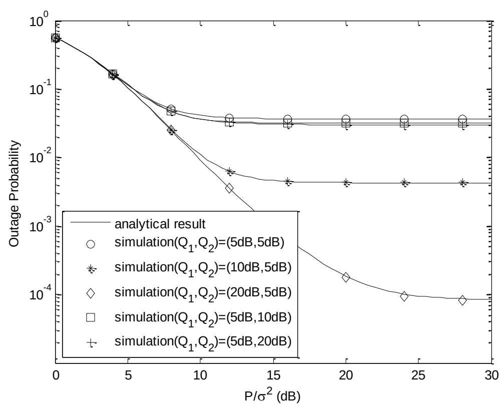

Fig. 4. Outage probability versus SNR P/σ^2 for ATP.

Fig. 4 shows the outage probability versus the SNR with ATP. In this simulation, the number of relay nodes N is set to 2. It can be seen that outage probability decreases slightly with the increasing of Q_2, whereas decreases sharply with the increasing of Q_1. This is because the direct channel has been considered in this system. For this reason, the system will choose the direct channel with greater probability to transmit signals when we increase Q_1, due to the cooperative channels are severely restricted by Q_2. Consequently, we can find that the direct channel played an important role in this system when the cooperative relay channels are subject to the strong limitation from the primary users. In addition, the outage floor has not been eliminated, but it has been reduced with increased Q_1 or Q_2.

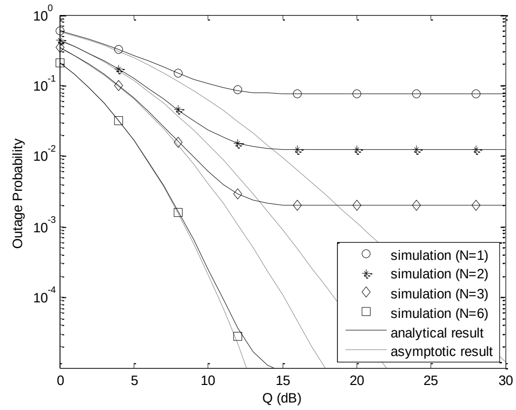

Fig. 5. Outage probability versus tolerable interference power for ATP $(Q_1 = Q_2 = Q)$.

Fig. 5 depicts the outage probability versus the tolerable interference power with ATP for $N = 1,2,3,6$. In this simulation, the maximum transmit power P is set to $12\,\mathrm{dB}$, and the tolerance interference power

$Q_1 = Q_2 = Q$. In this figure, the solid lines correspond to closed-form expression and the dotted lines correspond to asymptotic expression at high SNR. It is clear that the analytical results are just in line with the simulated results. On the other hand, we can find that the outage probability decreases with increased N, as expected. Moreover, the asymptotic results decrease almost linearly with Q.

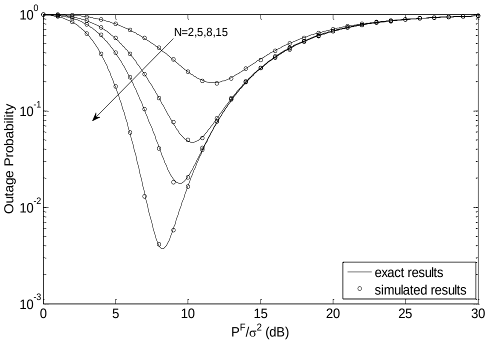

Fig. 6. Outage probability versus SNR P^{F}/σ^2 for FTP.

Fig. 6 depicts the outage probability versus SNR with FTP. In this simulation, we assume that all transmitters use the same fixed transmit power, i.e., $P_{\mathrm{S}}^{\mathrm{F}} = P_{\mathrm{R}}^{\mathrm{F}} = P^{\mathrm{F}}$, and the number of relays $N = 2, 5, 8, 15$. We observe that when the number of relays increases the outage performances of the secondary systems improve. It is important to note that there is an optimum SNR in each scheme for a certain number of relays, and the deterioration of outage performance due to the continuously rise the transmit power is rapid. This is due to the fact that the secondary system will be not always performed, and it will be paused when instantaneous interference from S to PU_1 above a certain threshold.

In Fig. 7, we compare the outage performance of the relaying scheme with ATP and FTP, respectively for the number of relays $N = 2, 5$. It can be easily seen that the ATP scheme performs better than the FTP scheme, especially at the high SNR district. This is mainly because at high SNR, due to the interference constraint, the FTP system will not performs while the ATP system could adjust its transmit power to satisfy the interference constraint and keep on working.

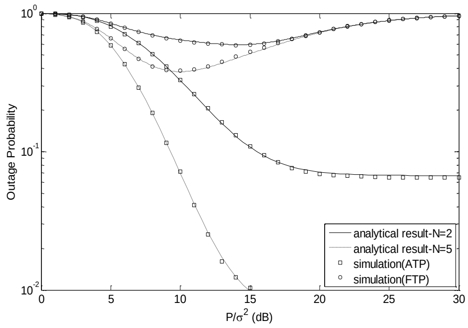

Fig. 7. Outage probability comparison of FTP and ATP.

In Fig. 8, we compare the outage performance of cognitive cooperative systems with different interference constraints. In this simulation, the number of relay nodes N is set to 3. Actually, when $Q_1 = Q_2 \to \infty$, this system can be viewed as a conventional cooperative system due to it ignores the interference constraint from primary users. We observe that the presence of primary largely deteriorates the outage performances of the secondary network in both ATP and FTP schemes. Moreover, in the absence of primary users, ATP and FTP have the same outage performance and the same diversity gain.

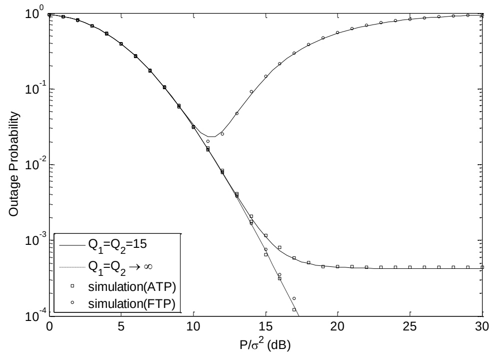

Fig. 8. Outage probability comparison for different Q_1, Q_2.

VI. Conclusion

This paper showed that cooperative diversity provides an effective approach to improve the transmission performance of the secondary user while ensuring the QoS of the primary user. We have proposed an adaptive cooperation diversity scheme with best-relay selection in multiple-relay cognitive radio networks where two primary users are coexisting with the secondary system. Furthermore, the effects of ATP and FTP power strategies on system performance were investigated, and the exact closed-form expressions and the asymptotic expressions for the secondary outage probability are derived for both schemes. Finally, we compare the performance of the system with different power schemes. Our results show that ,firstly, the system performance can be improved with increasing the number of relays, and the outage floor will not disappear but reduce with increased Q_1, Q_2, and N. Furthermore, Q_1 has a greater impact on this communication system than Q_2 because the direct channel has been considered in this system. In addition, the outage performance of the system with ATP is better than the system with FTP, especially at the large SNR district. However, the use of FTP requires less signaling overhead than the use of ATP.

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