An Adaptive Cooperation Diversity Scheme With Best-Relay Selection in Cognitive Radio Networks

Yulong Zou, Jia Zhu, Baoyu Zheng, and Yu-Dong Yao

***Abstract*—In this correspondence, an adaptive cooperation diversity scheme with best-relay selection is proposed for multiple-relay cognitive radio networks to improve the performance of secondary transmissions while ensuring the quality of service (QoS) of primary transmissions. Exact closed-form expressions of the outage probability of secondary transmissions, referred to as *secondary outage probability*, are derived under the constraint of satisfying a required outage probability of primary transmissions (*primary outage probability*) for both the traditional non-cooperation and the proposed adaptive cooperation schemes over Rayleigh fading channels. Numerical and simulation results show that, with a guaranteed primary outage probability, a floor of the secondary outage probability occurs in high signal-to-noise ratio (SNR) regions. Moreover, the outage probability floor of the adaptive cooperation scheme is lower than that of the non-cooperation scenario, which illustrates the advantage of the proposed scheme. In addition, we generalize the traditional definition of the diversity gain, which can not be applied directly in cognitive radio networks since mutual interference between the primary and secondary users should be considered. We derive the generalized diversity gain and show that, with a guaranteed primary outage probability, the full diversity order is achieved using the proposed adaptive cooperation scheme.**

***Index Terms*—Adaptive cooperation diversity, cognitive radio, diversity gain, outage probability, relay selection.**

I. INTRODUCTION

Cognitive radio (CR) is emerging as a promising technology to improve the utilization of wireless spectrum resources [1]. For its implementation, *interference temperature* has been proposed [1], [2] as a metric to quantify and manage the interference in a radio environment. A secondary user (SU) and a primary user (PU) can access a licensed spectrum simultaneously as long as the induced interference from SU to PU is below a threshold, i.e., the quality of service (QoS) of primary transmissions is not affected [2]. Therefore, the transmit power of SU is constrained to guarantee the PU's QoS. However, when the QoS requirement is stringent, very low transmit power level is allowed for SU and thus the SU's throughput is limited.

Cooperative diversity [3], emerging as a new spatial diversity technique, can effectively combat channel fading and enhance the throughput. The advantages of such cooperative diversity protocols proposed in [3]–[6] come at the expense of a reduction in spectral efficiency since the cooperative relays shall transmit on orthogonal channels. To overcome the shortcoming of the inefficient spectral utilization, the relay-selection-based cooperative diversity has been investigated in [7]–[9], where only the "best" relay is selected to forward a source node's signal and thus only two channels (i.e., the best relay link and direct link) are required regardless of the number of relays. It has been shown that the cooperative diversity with best-relay selection can achieve the same diversity-multiplexing tradeoff as achieved by the traditional cooperation protocols where all relays are involved in forwarding the source node's signal [3], [4]. Notice that all the research papers mentioned above [3]–[9] address the conventional non-cognitive radio networks.

Cooperation, in general, also has great potential to be used in cognitive radio networks. In [10], the authors have explored the application of cooperative diversity to spectrum sensing, and shown that the sensing performance is improved by exploiting the user cooperation. In [11], a linear cooperative sensing framework has been proposed based on the combination of local statistics from individual cognitive users. In [12] and [13], the authors have considered a secondary transmitter to act as a relay for primary transmissions. It has been shown that the secondary link throughput can be improved in certain network topologies. More recently, papers [14] and [15] have investigated the use of cooperative relay to assist the fulfillment of heterogeneous traffic demands in a secondary network with an unbalanced spectrum usage.

The main contributions of this correspondence are described as follows. First, unlike the previous research about relay selection in conventional networks, we investigate the adaptive cooperation diversity with best-relay selection in cognitive radio networks, where mutual interference between PU and SU are considered. Second, an exact closed-form expression of the secondary outage probability is derived under the constraint of satisfying a required primary outage probability. Finally, we propose a generalized definition of the diversity gain in cognitive radio networks and show that the full diversity is achieved by the proposed scheme with a primary outage probability constraint.

The remainder of this correspondence can be described as follows. In Section II, we propose an adaptive cooperation diversity scheme with best-relay selection for cognitive radio networks, followed by Section III, where an outage probability analysis is presented for the proposed scheme along with the numerical evaluations. Section IV proposes a generalized definition of the diversity gain and illustrates that, with a guaranteed primary outage probability, the full diversity order can still be achieved. Finally, in Section V, we provide some concluding remarks.

II. PROPOSED ADAPTIVE COOPERATION SCHEME IN COGNITIVE RADIO NETWORKS

A. System Model

Consider a cognitive radio system with the coexistence of primary and secondary networks, as depicted in Fig. 1. In the primary network, a primary transmitter (PT) sends data to a primary destination (PD). Meanwhile, in the secondary network, a secondary transmitter (ST) transmits its data to a secondary destination (SD) simultaneously with the primary transmissions over the same channel. Notice that M secondary relays (SRs) denoted by $\mathcal{R} = \{\mathrm{SR}_i | i = 1, 2, \cdots, M\}$ are available to assist ST's data transmissions and the decode-and-forward protocol is considered throughout this correspondence. As can be observed from Fig. 1(a), primary and secondary networks would affect each other. In order to guarantee the QoS of primary transmissions, the

Manuscript received October 17, 2009; accepted June 12, 2010. Date of publication June 21, 2010; date of current version September 15, 2010. The associate editor coordinating the review of this manuscript and approving it for publication was Dr. Shengli Zhou. This work was partially supported by the Postgraduate Innovation Program of Scientific Research of Jiangsu Province (Grants CX08B_080Z, CX09B_150Z) and the National Natural Science Foundation of China (Grant 60972039).

Y. Zou is with the Institute of Signal Processing and Transmission, Nanjing University of Posts and Telecommunications, Nanjing, Jiangsu 210003, China, and also with the Electrical and Computer Engineering Department, Stevens Institute of Technology, Hoboken, NJ 07030 USA (e-mail: zouyulong198412@126.com; yzou1@stevens.edu).

J. Zhu and B. Zheng are with the Institute of Signal Processing and Transmission, Nanjing University of Posts and Telecommunications, Nanjing, Jiangsu 210003, China.

Y.-D. Yao is with the Electrical and Computer Engineering Department, Stevens Institute of Technology, Hoboken, NJ 07030 USA.

This paper has supplementary downloadable multimedia material available at http://ieeexplore.org provided by the authors.

Color versions of one or more of the figures in this correspondence are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TSP.2010.2053708

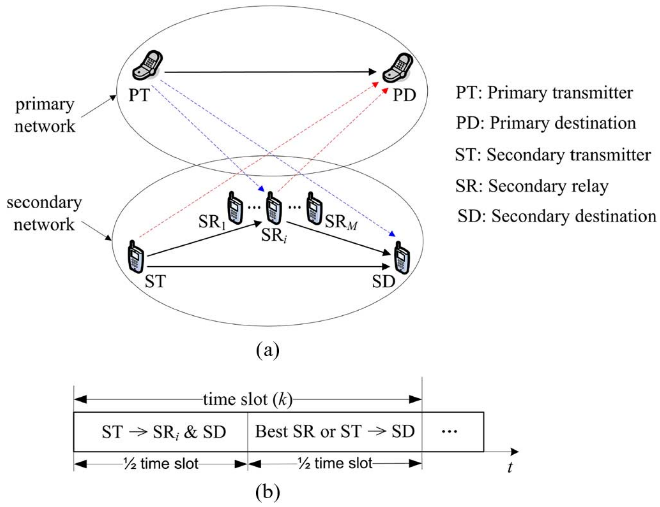

Fig. 1. (a) Cognitive radio system with coexistence of primary and secondary networks; (b) illustration of the transmission process for the proposed adaptive cooperation with best-relay selection.

transmit power of ST should be limited for reducing the interference to PD.

Fig. 1(b) illustrates the transmission process of the proposed adaptive cooperation scheme, where each time slot is divided into two half subtime-slots (subphases). In the first subphase, ST sends (broadcasts) its signal to SRs and SD. Then, all SRs attempt to decode the ST's signal and those SRs which decode successfully constitute a set D, referred to as a *decoding set*. Accordingly, the sample space of all the possible decoding sets can be written as

$$\Omega = \{\emptyset \cup D_m, \quad m = 1, 2, \cdots, 2^M - 1\} \tag{1}$$

where $\cup$ represents an union operation, $\emptyset$ is an empty set, and D_m is a non-empty subcollection of the M secondary relays. In the second subphase, if the decoding set (D) is not empty, the "best" relay (see Section II-B) chosen within the decoding set will forward its decoded result to SD. If D is empty, i.e., no relay is able to decode the ST's signal successfully, ST will repeat the transmission of the original signal to SD through the direct link. Finally, SD combines the two copies of the received signals using the maximum ratio combining (MRC) method, and gives an estimation of the original signal after a maximum likelihood decision (MLD). Notice that in order to satisfy the primary QoS requirement, the transmit power of both the ST and the best SR shall be limited.

Assume that PT transmits signal x_p $(\mathrm{E}[|x_p|^2] = 1)$ to PD with a fixed power P_{PT} and data rate R_p in time slot k and, in the meantime, ST intends to reuse this time slot to transmit its signal x_s $(\mathrm{E}[|x_s|^2] = 1)$ to SD with power P_{ST} and data rate R_s. The channels are modeled as Rayleigh fading that is invariant during one time slot. We assume that a SU (i.e., ST and SR) has the knowledge of the average (not instantaneous) channel gains of the link from itself to PD and the link from PT to PD. This is because that a general secondary network is typically not coordinated with the primary network and no dedicated feedback channel is available from a primary user to a secondary user, resulting in that the instantaneous channel gains of PUs are unavailable at a SU. However, the average channel gains of PUs can be estimated at the SU, since they are relatively stable and relate to the system parameters only, such as the transmission distance, transmit/receive antenna gain, wavelength of electromagnetic wave, and so on. In addition, we assume that a SR has the knowledge of the instantaneous channel gain of the link from itself to the SD, which is possible due to the fact that both SR and SD are within the same system with a possibly dedicated feedback channel. Thus, the received signal at SD during time slot k can be expressed as

$$y_{\mathrm{SD}} = \sqrt{P_{\mathrm{ST}}} h_{\mathrm{ST-SD}} x_s + \sqrt{P_{\mathrm{PT}}} h_{\mathrm{PT-SD}} x_p + n_{\mathrm{SD}} \tag{2}$$

where the time index k is dropped for notational convenience, $h_{\mathrm{ST-SD}}$ and $h_{\mathrm{PT-SD}}$ are the fading coefficients of the channel from ST to SD and that from PT to SD, respectively, and n_{SD} is an additive white Gaussian noise (AWGN) with zero mean and power spectral density N_0. Meanwhile, the received signal at PD can be expressed as

$$y_{\mathrm{PD}} = \sqrt{P_{\mathrm{PT}}} h_{\mathrm{PT-PD}} x_p + \sqrt{P_{\mathrm{ST}}} h_{\mathrm{ST-PD}} x_s + n_{\mathrm{PD}} \tag{3}$$

where $h_{\mathrm{PT-PD}}$ and $h_{\mathrm{ST-PD}}$ are the fading coefficients of the channel from PT to PD and that from ST to PD, respectively, and n_{PD} is an AWGN with zero mean and power spectral density N_0. Throughout this correspondence, we use outage probability performance to quantify the QoS of primary transmissions [17]. Specifically, the outage probability of primary transmissions (*primary outage probability*) shall be guaranteed to be below a predefined threshold $\mathrm{Pout}_{\mathrm{Pri,Thr}}$. Hence, following (3), we can calculate the primary outage probability [3], [4] as

$$\mathrm{Pout}_{\mathrm{Pri}} = \Pr\left(\log_2\left(1 + \frac{P_{\mathrm{PT}}|h_{\mathrm{PT-PD}}|^2}{P_{\mathrm{ST}}|h_{\mathrm{ST-PD}}|^2 + N_0}\right) < R_p\right) \le \mathrm{Pout}_{\mathrm{Pri,Thr}}. \tag{4}$$

Notice that random variables (RVs) $x = |h_{\mathrm{PT-PD}}|^2$ and $y = |h_{\mathrm{ST-PD}}|^2$ follow the exponential distributions with parameters $1/\sigma^2_{\mathrm{PT-PD}}$ and $1/\sigma^2_{\mathrm{ST-PD}}$, respectively, where $\sigma^2_{\mathrm{PT-PD}}$ and $\sigma^2_{\mathrm{ST-PD}}$ are the fading variances of the channel from PT to PD and that from ST to PD, respectively. Thus, from (4), using the joint probability density function (PDF) of RVs x and y, we have

$$\begin{aligned}\mathrm{Pout}_{\mathrm{Pri}} &= \iint\limits_{\gamma_{\mathrm{PT}}x - \gamma_{\mathrm{ST}}y\Theta < \Theta} \frac{1}{\sigma^2_{\mathrm{PT-PD}}\sigma^2_{\mathrm{ST-PD}}} \\ &\qquad \times \exp\left(-\frac{x}{\sigma^2_{\mathrm{PT-PD}}} - \frac{y}{\sigma^2_{\mathrm{ST-PD}}}\right) dxdy \\ &= 1 - \frac{\gamma_{\mathrm{PT}}\sigma^2_{\mathrm{PT-PD}}}{\gamma_{\mathrm{ST}}\sigma^2_{\mathrm{ST-PD}}\Theta + \gamma_{\mathrm{PT}}\sigma^2_{\mathrm{PT-PD}}} \exp\left(-\frac{\Theta}{\gamma_{\mathrm{PT}}\sigma^2_{\mathrm{PT-PD}}}\right)\end{aligned}$$

where $\Theta = 2^{R_p} - 1$, and $\gamma_{\mathrm{PT}} = P_{\mathrm{PT}}/N_0$ and $\gamma_{\mathrm{ST}} = P_{\mathrm{ST}}/N_0$ are regarded as the transmit signal-to-noise ratio (SNR) at PT and ST, respectively. Substituting $\mathrm{Pout}_{\mathrm{Pri}}$ from the preceding equation into (4) yields

$$\begin{aligned}P_{\mathrm{ST}} \le &\frac{\sigma^2_{\mathrm{PT-PD}} P_{\mathrm{PT}}}{\sigma^2_{\mathrm{ST-PD}}\Theta} \\ &\times \left[\frac{1}{1 - \mathrm{Pout}_{\mathrm{Pri,Thr}}} \exp\left(-\frac{\Theta}{\sigma^2_{\mathrm{PT-PD}}\gamma_{\mathrm{PT}}}\right) - 1\right].\end{aligned} \tag{5}$$

As is evident from (5), if $\mathrm{Pout}_{\mathrm{Pri,Thr}} < 1 - \exp(-(\Theta/\sigma^2_{\mathrm{PT-PD}}\gamma_{\mathrm{PT}}))$ occurs due to large-scale propagation losses of the primary channels, the secondary transmit power P_{ST} should be set to zero, which implies that the primary channel is unavailable for the secondary transmitter which needs to seek another transmission opportunity. In this correspondence, we focus on investigating the effect of adaptive cooperation diversity in cognitive radio networks without detailed considerations of any adaptive power control schemes [16]. Hence, without loss of generality, we adopt a static method to control the ST's transmit power, i.e., ST utilizes the maximum average power allowed to transmit its data, i.e.,

$$P_{\mathrm{ST}} = \frac{\sigma^2_{\mathrm{PT-PD}} P_{\mathrm{PT}}}{\sigma^2_{\mathrm{ST-PD}} \Theta} \rho^+ \tag{6}$$

where $\rho^+ = \max(\rho, 0)$ and $\rho = (1/(1 - \mathrm{Pout}_{\mathrm{Pri,Thr}}) \times \exp(-(\Theta/\sigma^2_{\mathrm{PT-PD}} \gamma_{\mathrm{PT}})) - 1$. The reasons for using an average channel gain based power control approach are twofold. First, ST is typically unable to obtain the instantaneous channel gains (also called instantaneous fading) of PUs, since a general secondary network is not coordinated with the primary network and no dedicated channel is available for such channel information feedback from a primary user to a secondary user. In contrast to the fast variation of instantaneous fading, the average channel gains of PUs are relatively stable and can be estimated at the SU, which can save the feedback channel resources. Second, compared with an instantaneous fading based power control algorithm, the benefit of the proposed power control approach using average channel gains as given by (6) is that it allows power allocation to be performed on the far longer time scale of log-normal shadowing instead of the time scale of Rayleigh fading [17]. Moreover, in some practical communication scenarios with high terminal speed [17], the channel varies rapidly and undergoes fast fading. In such a case, it is difficult to estimate the instantaneous fading states and, most importantly, more channel resources are needed for the fast fading state feedback.

B. Proposed Adaptive Cooperation With Best-Relay Selection

This subsection focuses on the best-relay selection issue in cognitive radio networks. Presently, in [7]–[9], the authors investigated the best-relay selection in traditional non-cognitive radio networks, where the relay selection criteria only consider the channel state information (CSI) of the two-hop relaying link from source via relay to destination. However, we attempt to explore the adaptive cooperation diversity with best-relay selection in cognitive radio networks, in which the best-relay selection considers not only the CSI of two-hop relaying link, but also the condition of the link from secondary relay to primary destination. This is due to the fact that in cognitive radio networks, the interference from secondary relay to primary destination shall be limited to satisfy a given primary QoS requirement. Thus, the channel condition of the link from SR to PD should be taken into account for the best-relay selection, in addition to the two-hop relaying link condition.

As has been discussed in Section II-A, each transmission process of the adaptive cooperation scheme is divided into two half subphases. In the first subphase of time slot k, the received signal at the candidate relay SR_i and SD are expressed as

$$y_{\mathrm{SR}_i}(k,1) = \sqrt{P_{\mathrm{ST}}} h_{\mathrm{ST-SR}_i} x_s + \sqrt{P_{\mathrm{PT}}} h_{\mathrm{PT-SR}_i} x_p + n_{\mathrm{SR}_i} \tag{7}$$
$$y_{\mathrm{SD}}(k,1) = \sqrt{P_{\mathrm{ST}}} h_{\mathrm{ST-SD}} x_s + \sqrt{P_{\mathrm{PT}}} h_{\mathrm{PT-SD}} x_p + n_{\mathrm{SD}} \tag{8}$$

where P_{ST} is given by (6), $h_{\mathrm{ST-SR}_i}$ and $h_{\mathrm{PT-SR}_i}$ are the fading coefficients of the channel from ST to SR_i and that from PT to SR_i, respectively. Here, we assume that to meet a required primary outage probability, the SUs including both the secondary transmitter and secondary relays should guarantee that the outage probability perceived by the primary destination in each subphase satisfies the same outage probability constraint $\mathrm{Pout}_{\mathrm{Pri,Thr}}$. In the second subphase, there are two possible cases for the data transmission depending on whether the decoding set (D) is empty or not. For simplicity, let $D = \emptyset$ represent the first case of an empty decoding set and $D = D_m$ correspond to the other case, where D_m is a non-empty subcollection of all M secondary relays.

- Case $D = \emptyset$: This case corresponds to all the candidate relays failing to decode the ST's signal, which is indicated by the following event (in an information-theoretic sense),

$$\frac{1}{2}\log_2\left(1+\frac{P_{\mathrm{ST}}\left|h_{\mathrm{ST-SR}_i}\right|^2}{P_{\mathrm{PT}}\left|h_{\mathrm{PT-SR}_i}\right|^2+N_0}\right)< R_s, \quad i\in\{1,2,\cdots,M\} \tag{9}$$

  where the factor 1/2 in the front of log-function is due to the fact that two channels (i.e., two half subtime-slots) are needed to complete each transmission. In this case, ST will repeat the transmission of the original signal x_s through the direct link. Thus, in the second subphase of time slot k, the received signal at SD can be expressed as

$$y_{\mathrm{SD}}(k,2|D=\emptyset) = \sqrt{P_{\mathrm{ST}}} h_{\mathrm{ST-SD}} x_s + \sqrt{P_{\mathrm{PT}}} h_{\mathrm{PT-SD}} x_p + n_{\mathrm{SD}}. \tag{10}$$

  Combining (8) and (10) with MRC, we can obtain the corresponding received signal-to-interference-and-noise ratio (SINR) at SD as

$$\mathrm{SINR}_{\mathrm{SD}}(D=\emptyset) = \frac{2P_{\mathrm{ST}}|h_{\mathrm{ST-SD}}|^2}{P_{\mathrm{PT}}|h_{\mathrm{PT-SD}}|^2 + N_0} \tag{11}$$

  where P_{ST} is given in (6).
- Case $D = D_m$: This case corresponds to the relays in decoding set D_m being able to decode the ST's signal successfully, i.e.,

$$\frac{1}{2}\log_2\left(1+\frac{P_{\mathrm{ST}}\left|h_{\mathrm{ST-SR}_i}\right|^2}{P_{\mathrm{PT}}\left|h_{\mathrm{PT-SR}_i}\right|^2+N_0}\right)> R_s, \quad i\in D_m$$
$$\frac{1}{2}\log_2\left(1+\frac{P_{\mathrm{ST}}\left|h_{\mathrm{ST-SR}_j}\right|^2}{P_{\mathrm{PT}}\left|h_{\mathrm{PT-SR}_j}\right|^2+N_0}\right)< R_s, \quad j\in \bar{D}_m \tag{12}$$

  where $\bar{D}_m = \mathcal{R} - D_m$ denotes the complementary set of D_m and P_{ST} is given by (6). Without loss of generality, consider that a candidate relay $\mathrm{SR}_i \in D_m$ is selected to forward its correctly decoded result. Hence, the received signal at SD in the second subphase can be written as

$$y_{\mathrm{SD}}(k,2|D=D_m) = \sqrt{P_{\mathrm{SR}_i}} h_{\mathrm{SR}_i-\mathrm{SD}} x_s + \sqrt{P_{\mathrm{PT}}} h_{\mathrm{PT-SD}} x_p + n_{\mathrm{SD}} \tag{13}$$

  where P_{SR_i} is the transmit power of the selected SR_i, which is found as

$$P_{\mathrm{SR}_i} = \frac{\sigma^2_{\mathrm{PT-PD}} P_{\mathrm{PT}}}{\sigma^2_{\mathrm{SR}_i-\mathrm{PD}} \Theta} \rho^+ \tag{14}$$

  Therefore, given that case $D = D_m$ has occurred and the candidate relay SR_i is selected, we can calculate the corresponding received SINR at SD by combining (8) and (13) with MRC as

$$\mathrm{SINR}_{\mathrm{SD}}(D=D_m,\mathrm{SR}_i) = \frac{P_{\mathrm{ST}}|h_{\mathrm{ST-SD}}|^2}{P_{\mathrm{PT}}|h_{\mathrm{PT-SD}}|^2 + N_0} + \frac{P_{\mathrm{SR}_i}|h_{\mathrm{SR}_i-\mathrm{SD}}|^2}{P_{\mathrm{PT}}|h_{\mathrm{PT-SD}}|^2 + N_0}. \tag{15}$$

In general, the relay, which can successfully decode the ST's signal and can achieve the highest received SINR at SD, is viewed as the "best" one. As a consequence, the best-relay selection criterion can be written as

$$\begin{aligned}\text{Best relay} &= \arg\max_{i\in D_m} \mathrm{SINR}_{\mathrm{SD}}(D=D_m,\mathrm{SR}_i)\\ &= \arg\max_{i\in D_m} \frac{|h_{\mathrm{SR}_i-\mathrm{SD}}|^2}{\sigma^2_{\mathrm{SR}_i-\mathrm{PD}}}\end{aligned} \tag{16}$$

which shows that the proposed best-relay selection criterion takes into account not only the two-hop relaying link condition, but also the condition of the link from secondary relay to primary destination, differing from [7]–[9] where only the two-hop relaying link condition is used for best-relay selection. It is pointed out that using the best-relay selection criterion as shown in (16), we are able to further develop a specific relay selection algorithm in a centralized or distributed approach. More specifically, for a centralized relay selection, the secondary source node should maintain a table that consists of all the secondary relays and the related channel information (i.e., $|h_{\mathrm{SR}_i-\mathrm{SD}}|^2$ and $\sigma^2_{\mathrm{SR}_i-\mathrm{PD}}$). After that, the best relay can be easily determined by looking up the table using the proposed criterion. Such an approach is called centralized relay selection strategy. For a distributed relay selection, each secondary relay should maintain a timer [7] and set an initial value of the timer in inverse proportional to the term $|h_{\mathrm{SR}_i-\mathrm{SD}}|^2/\sigma^2_{\mathrm{SR}_i-\mathrm{PD}}$ as given in (16), resulting in the best relay with the smallest initial value for its timer. Therefore, the best relay exhausts its timer earliest compared with the other relays, and then broadcasts a control packet to notify the source node and other relays [7].

III. Outage Analysis of the Proposed Scheme Over Rayleigh Fading Channels

In this section, we analyze the outage probability performance for the adaptive cooperation diversity scheme. For the purpose of comparison, let us consider first the traditional non-cooperative transmission scheme. From (2), we can calculate the outage probability of secondary transmissions (*secondary outage probability*) for the non-cooperation scheme as

$$\mathrm{Pout}_{\mathrm{direct}} = \Pr\left(\log_2\left(1+\frac{|h_{\mathrm{ST-SD}}|^2\gamma_{\mathrm{ST}}}{|h_{\mathrm{PT-SD}}|^2\gamma_{\mathrm{PT}}+1}\right)<R_s\right). \tag{17}$$

Notice that RVs $|h_{\mathrm{ST-SD}}|^2$ and $|h_{\mathrm{PT-SD}}|^2$ follow the exponential distributions with parameters $1/\sigma^2_{\mathrm{ST-SD}}$ and $1/\sigma^2_{\mathrm{PT-SD}}$, respectively. Solving the probability integral in (17) yields

$$\begin{aligned}\mathrm{Pout}_{\mathrm{direct}} = 1 - &\frac{\sigma^2_{\mathrm{ST-SD}}\gamma_{\mathrm{ST}}}{\sigma^2_{\mathrm{ST-SD}}\gamma_{\mathrm{ST}}+\sigma^2_{\mathrm{PT-SD}}\gamma_{\mathrm{PT}}\Delta}\\ &\times\exp\left(-\frac{\Delta}{\sigma^2_{\mathrm{ST-SD}}\gamma_{\mathrm{ST}}}\right)\end{aligned} \tag{18}$$

where $\Delta = 2^{R_s}-1$. Following (6) and (18) and considering $\gamma_{\mathrm{PT}}\to+\infty$, we obtain (19), shown at the bottom of the page. As can be observed from (19), the outage probability becomes a non-zero constant as the transmit SNR γ_{PT} approaches to infinity, i.e., an outage probability floor occurs. This is due to the fact that when the transmit SNR γ_{PT} is high, the interference from PT becomes the dominant factor to induce an outage event in secondary channels. Therefore, in high γ_{PT} regions, it is not feasible to improve the outage probability performance through increasing the transmit power, which also motivates us to explore approaches to reduce the outage probability floor. In what follows, we focus on the outage analysis for the proposed adaptive cooperation scheme.

- Case $D=\emptyset$: Following (10), the occurrence probability of case $D=\emptyset$ is given by

$$\begin{aligned}\Pr(D=\emptyset) = \prod_{i=1}^{M}\Bigg(1-&\frac{\sigma^2_{\mathrm{ST-SR}_i}\gamma_{\mathrm{ST}}}{\sigma^2_{\mathrm{ST-SR}_i}\gamma_{\mathrm{ST}}+\sigma^2_{\mathrm{PT-SR}_i}\gamma_{\mathrm{PT}}\Lambda}\\ &\times\exp\left(-\frac{\Lambda}{\sigma^2_{\mathrm{ST-SR}_i}\gamma_{\mathrm{ST}}}\right)\Bigg)\end{aligned} \tag{20}$$

where $\Lambda = 2^{2R_s}-1$, $\gamma_{\mathrm{ST}}=P_{\mathrm{ST}}/N_0$ and P_{ST} is given by (6). Clearly, given that case $D=\emptyset$ has occurred, it is shown from (11) that the conditional secondary outage probability for the proposed adaptive cooperation scheme is given by

$$\begin{aligned}\Pr(\mathrm{outage}|D=\emptyset) = 1-&\frac{2\sigma^2_{\mathrm{ST-SD}}\gamma_{\mathrm{ST}}}{2\sigma^2_{\mathrm{ST-SD}}\gamma_{\mathrm{ST}}+\sigma^2_{\mathrm{PT-SD}}\gamma_{\mathrm{PT}}\Lambda}\\ &\times\exp\left(-\frac{\Lambda}{2\sigma^2_{\mathrm{ST-SD}}\gamma_{\mathrm{ST}}}\right).\end{aligned} \tag{21}$$

- Case $D=D_m$: From (14), the occurrence probability of case $D=D_m$ can be found as

$$\begin{aligned}\Pr(D=D_m) = &\prod_{i\in D_m}\frac{\sigma^2_{\mathrm{ST-SR}_i}\gamma_{\mathrm{ST}}}{\sigma^2_{\mathrm{ST-SR}_i}\gamma_{\mathrm{ST}}+\sigma^2_{\mathrm{PT-SR}_i}\gamma_{\mathrm{PT}}\Lambda}\\ &\times\exp\left(-\frac{\Lambda}{\sigma^2_{\mathrm{ST-SR}_i}\gamma_{\mathrm{ST}}}\right)\\ &\times\prod_{j\in\bar{D}_m}\Bigg[1-\frac{\sigma^2_{\mathrm{ST-SR}_j}\gamma_{\mathrm{ST}}}{\sigma^2_{\mathrm{ST-SR}_j}\gamma_{\mathrm{ST}}+\sigma^2_{\mathrm{PT-SR}_j}\gamma_{\mathrm{PT}}\Lambda}\\ &\times\exp\left(-\frac{\Lambda}{\sigma^2_{\mathrm{ST-SR}_j}\gamma_{\mathrm{ST}}}\right)\Bigg].\end{aligned} \tag{22}$$

Given that case $D=D_m$ has occurred, the conditional secondary outage probability of the adaptive cooperation can be calculated as

$$\begin{aligned}\Pr(\mathrm{outage}|D=D_m) = \Pr\Bigg(&\frac{1}{2}\log_2\Big[1\\ &+\max_{i\in D_m}\mathrm{SINR}_{\mathrm{SD}}(D=D_m,\mathrm{SR}_i)\Big]<R_s\Bigg)\end{aligned} \tag{23}$$

$$\mathrm{Pout}_{\mathrm{direct,floor}} = \lim_{\gamma_{\mathrm{PT}}\to+\infty}\mathrm{Pout}_{\mathrm{direct}} = \frac{\sigma^2_{\mathrm{PT-SD}}\sigma^2_{\mathrm{ST-PD}}\Delta\Theta(1-\mathrm{Pout}_{\mathrm{Pri,Thr}})}{\sigma^2_{\mathrm{PT-SD}}\sigma^2_{\mathrm{ST-PD}}\Delta\Theta(1-\mathrm{Pout}_{\mathrm{Pri,Thr}})+\sigma^2_{\mathrm{ST-SD}}\sigma^2_{\mathrm{PT-PD}}\mathrm{Pout}_{\mathrm{Pri,Thr}}} \tag{19}$$

where $\mathrm{SINR}_{\mathrm{SD}}(D = D_m, \mathrm{SR}_i)$ is given in (15). Using the results of Appendix A, we are able to obtain from the preceding equation as

$$\Pr(\mathrm{outage}|D = D_m) = \mathrm{A}_m + \mathrm{B}_m \tag{24}$$

where the terms A_m and B_m are given by

$$\mathrm{A}_m = \Gamma + \sum_{n=1}^{2^{\|D_m\|}-1} \frac{(-1)^{\|S_m(n)\|}\Gamma}{1 + \sigma^2_{\mathrm{PT-SD}}\gamma_{\mathrm{PT}}\Psi_{S_m(n)}} \exp\left(-\Psi_{S_m(n)}\right) \tag{25}$$

and

$$\mathrm{B}_m = (1-\Gamma)\left[1 - \exp\left(-\frac{\Lambda}{\sigma^2_{\mathrm{ST-SD}}\gamma_{\mathrm{ST}}}\right) + \sum_{n=1}^{2^{\|D_m\|}-1} (-1)^{\|S_m(n)\|}\Phi_{S_m(n)}\right] \tag{26}$$

where $\Gamma = \sigma^2_{\mathrm{PT-SD}}\Lambda\gamma_{\mathrm{PT}}/(\sigma^2_{\mathrm{PT-SD}}\Lambda\gamma_{\mathrm{PT}} + \sigma^2_{\mathrm{ST-SD}}\gamma_{\mathrm{ST}})$, $\Psi_{S_m(n)} = \sum_{i\in S_m(n)}(\Lambda/\sigma^2_{\mathrm{SR}_i-\mathrm{SD}}\gamma_{\mathrm{SR}_i})$, and $\Phi_{S_m(n)}$ is given by (27), shown at the bottom of the page, where $\|D_m\|$ is the number of elements in the decoding set D_m and $S_m(n)$ is the nth non-empty subcollection of the elements in D_m. Using the total probability law, we can easily obtain an exact expression of the secondary outage probability for the proposed adaptive cooperation scheme as

$$\mathrm{Pout}_{\mathrm{multi}} = \Pr(D = \emptyset)\Pr(\mathrm{outage}|D = \emptyset) + \sum_{m=1}^{2^M-1} \Pr(D = D_m)\Pr(\mathrm{outage}|D = D_m) \tag{28}$$

where $\Pr(D = \emptyset)$, $\Pr(\mathrm{outage}|D = \emptyset)$, $\Pr(D = D_m)$ and $\Pr(\mathrm{outage}|D = D_m)$ are given by (20), (21), (22), and (24), respectively.

Fig. 2 shows the secondary outage probability versus the transmit SNR γ_{PT} of the non-cooperation and the adaptive cooperation schemes, where the lines are plotted by using (18) and (28). Also, the computer simulation results are illustrated in the figure. It can be seen from Fig. 2 that there is a *cutoff* point for the transmit SNR γ_{PT}, i.e., if γ_{PT} is smaller than a cutoff value (i.e., $\gamma_{\mathrm{cutoff}} = 10$ dB), the secondary outage probability equals one, which means that no secondary transmission is allowed. Notice that the cutoff values of the transmit SNR γ_{PT} for both the non-cooperation and the adaptive cooperation schemes are identical, which is due to the fact that we only consider the non-cooperation scenario for primary transmissions. In the case that only the non-cooperation approach is used for the primary transmissions, the allowable secondary transmit power for the adaptive cooperation scheme is the same as that for the non-cooperation scheme. One can observe from (5) that the cutoff value of the transmit SNR γ_{PT} depends on various factors such as the primary outage probability requirement, the primary data rate, and the channel gain from primary transmitter to primary destination. Typically, the cutoff value of the transmit SNR γ_{PT} can be reduced through improving the primary outage probability by using an advanced transmission technique (such as, MIMO, cooperative diversity and so on) for the primary communications.

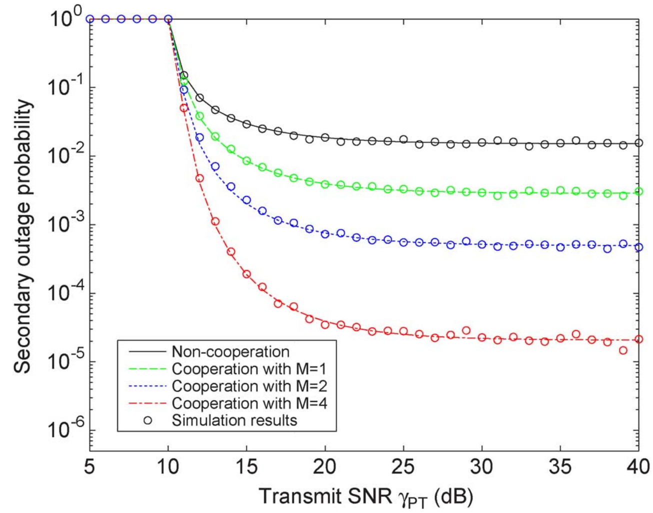

Fig. 2. Illustration of the secondary outage probability versus the transmit SNR γ_{PT} with a guaranteed primary outage probability threshold $\mathrm{Pout}_{\mathrm{Pri,Thr}} = 0.03$, primary data rate $R_p = 0.4$ bits/s/Hz, secondary data rate $R_s = 0.2$ bits/s/Hz, $\sigma^2_{\mathrm{PT-PD}} = \sigma^2_{\mathrm{ST-SD}} = \sigma^2_{\mathrm{ST-SR}_i} = \sigma^2_{\mathrm{SR}_i-\mathrm{SD}} = 1$, $\sigma^2_{\mathrm{PT-SD}} = \sigma^2_{\mathrm{ST-PD}} = 0.1$, and $\sigma^2_{\mathrm{PT-SR}_i} = \sigma^2_{\mathrm{SR}_i-\mathrm{PD}} = 0.2$.

From Fig. 2, one can observe that an outage probability floor occurs in high γ_{PT} regions, which is due to the fact that when the transmit SNR γ_{PT} is high, the interference from the primary transmissions becomes the dominant factor to induce a channel outage. Moreover, the outage probability floor of the adaptive cooperation scheme is lower than that of the non-cooperation scheme, which illustrates the advantage of the proposed scheme. It is also shown from Fig. 2 that, with a guaranteed primary outage probability threshold $\mathrm{Pout}_{\mathrm{Pri,Thr}} = 0.03$, the secondary outage probability of the adaptive cooperation scheme is improved as the number of the secondary relays increases. In addition, the simulation results match the analytical results very well.

In Fig. 3, we plot (18) and (28) as a function of the primary outage probability for both the non-cooperation and the adaptive cooperation schemes. Fig. 3 shows that there is a *cutoff* point for the primary outage probability, i.e., if the primary outage probability requirement is so stringent below a cutoff value, no secondary transmissions would be

$$\Phi_{S_m(n)} = \begin{cases} \dfrac{\Lambda}{\sigma^2_{\mathrm{ST-SD}}\gamma_{\mathrm{ST}}} \exp\left(-\dfrac{\Lambda}{\sigma^2_{\mathrm{ST-SD}}\gamma_{\mathrm{ST}}}\right), & \displaystyle\sum_{i\in S_m(n)} \frac{\sigma^2_{\mathrm{SR}_i-\mathrm{PD}}}{\sigma^2_{\mathrm{SR}_i-\mathrm{SD}}} = \frac{\sigma^2_{\mathrm{ST-PD}}}{\sigma^2_{\mathrm{ST-SD}}} \\ \dfrac{\exp\left(-\Psi_{S_m(n)}\right) - \exp\left(-\dfrac{\Lambda}{\sigma^2_{\mathrm{ST-SD}}\gamma_{\mathrm{ST}}}\right)}{1 - \displaystyle\sum_{i\in S_m(n)} \frac{\sigma^2_{\mathrm{ST-SD}}\sigma^2_{\mathrm{SR}_i-\mathrm{PD}}}{\sigma^2_{\mathrm{ST-PD}}\sigma^2_{\mathrm{SR}_i-\mathrm{SD}}}}, & \text{otherwise} \end{cases} \tag{27}$$

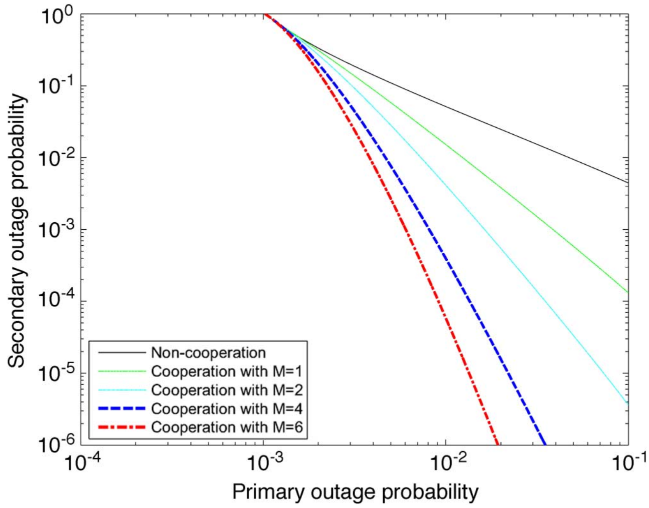

Fig. 3. Secondary outage probability versus primary outage probability of the non-cooperation and adaptive cooperation schemes with a primary data rate $R_p = 0.4$ bits/s/Hz, secondary data rate $R_s = 0.2$ bits/s/Hz, transmit SNR $\gamma_{\rm PT} = 25$ dB, $\sigma^2_{\rm PT-PD} = \sigma^2_{\rm ST-SD} = \sigma^2_{{\rm ST-SR}_i} = \sigma^2_{{\rm SR}_i-{\rm SD}} = 1$, $\sigma^2_{\rm PT-SD} = \sigma^2_{\rm ST-PD} = 0.1$, and $\sigma^2_{{\rm PT-SR}_i} = \sigma^2_{{\rm SR}_i-{\rm PD}} = 0.2$.

allowed. Similar to Fig. 2, the cutoff value of the primary outage probability for the non-cooperation is the same as that for the adaptive cooperation scheme, as only the non-cooperation scenario is considered for the primary transmissions. Furthermore, Fig. 3 illustrates that the secondary outage probability performance is improved as the primary QoS requirement loosens and, moreover, the adaptive cooperation scheme outperforms the non-cooperation scheme in terms of the secondary outage probability with a guaranteed primary outage probability. Notice that in Figs. 2 and 3, the mutual interference gains between primary and secondary users are assumed to be relatively small values (i.e., 0.1 and 0.2). With a required primary outage probability, the secondary outage performance will be degraded as the interference gains increase.

IV. Generalized Diversity Gain of the Adaptive Cooperation Scheme

In this section, we focus on the diversity gain analysis for the proposed adaptive cooperation scheme. As known in [18], the traditional diversity gain is defined as $d = -\lim_{\rm SNR\to+\infty} \log P_e({\rm SNR})/\log {\rm SNR}$, where no interference is taken into account. Hence, it is not appropriate to apply the traditional definition directly in cognitive radio networks since mutual interference between PU and SU should be considered. Following the traditional definition of the diversity gain, we analogously define a generalized diversity gain as an asymptotic ratio of the secondary outage probability floor to the interference gain $\sigma^2_{\rm ST-PD}$ with $\sigma^2_{\rm ST-PD} \to 0$, which is used to show the improvement of the secondary outage probability floor with an increasing number of the secondary relays. Accordingly, following (19), the generalized diversity gain of the non-cooperative transmission can be given by

$$d_{\rm direct} = \lim_{\sigma^2_{\rm ST-PD}\to 0} \frac{\log({\rm Pout}_{\rm direct,floor})}{\log\left(\sigma^2_{\rm ST-PD}\right)} = 1. \tag{29}$$

It is known that the interference from a SU transmitter to a PU receiver can approach to zero if this interference is mitigated as much as possible when the secondary system utilizes an advanced signal processing technique, such as beam forming. On the other hand, an interference cancellation approach may be employed at the SU receiver to reduce the interference from a PU transmitter, which, however, can not be cancelled out perfectly, i.e., the secondary outage probability floor will not be eliminated completely. Nevertheless, if the SU receiver has the ability to reduce such an interference so that it approaches to zero, the generalized diversity gain can be defined as an asymptotic ratio of the secondary outage probability floor to the interference gain $\sigma^2_{\rm PT-SD}$ with $\sigma^2_{\rm PT-SD} \to 0$, for which the same performance characteristic can be obtained. Moreover, if the SU receiver is assumed to perfectly cancel out the interference from the PU transmitter, we can use the traditional definition to analyze the diversity gain achieved by the proposed adaptive cooperation scheme in cognitive radio networks. Similar to (29), the diversity gain of the proposed adaptive cooperation scheme is defined as

$$d_{\rm multi} = \lim_{\sigma^2_{\rm ST-PD}\to 0} \frac{\log({\rm Pout}_{\rm multi,floor})}{\log\left(\sigma^2_{\rm ST-PD}\right)} \tag{30}$$

where the term ${\rm Pout}_{\rm multi,floor}$ is the result of ${\rm Pout}_{\rm multi}$ as $\gamma_{\rm PT} \to +\infty$, leading to

$$\begin{aligned}{\rm Pout}_{\rm multi,floor} &= \lim_{\gamma_{\rm PT}\to+\infty} \Pr(D=\emptyset)\Pr({\rm outage}|D=\emptyset)\\ &\quad + \sum_{m=1}^{2^M-1} \lim_{\gamma_{\rm PT}\to+\infty} \Pr(D=D_m)\Pr({\rm outage}|D=D_m).\end{aligned} \tag{31}$$

By combining (20) and (21) and considering $\sigma^2_{\rm ST-PD} \to 0$, the first term at the right-hand side of the preceding equation is given by

$$\begin{aligned}\lim_{\gamma_{\rm PT}\to+\infty} \Pr(D=\emptyset)\Pr({\rm outage}|D=\emptyset) &= \frac{\sigma^2_{\rm PT-SD}\xi^{M+1}}{2\sigma^2_{\rm ST-SD}}\\ &\times \prod_{i=1}^{M} \frac{\sigma^2_{{\rm PT-SR}_i}}{\sigma^2_{{\rm ST-SR}_i}} \cdot \left(\sigma^2_{\rm ST-PD}\right)^{M+1} + O\left(\sigma^2_{\rm ST-PD}\right)^{M+1}\end{aligned} \tag{32}$$

where $\xi = \Lambda\Theta(1-{\rm Pout}_{\rm Pri,Thr})/(\sigma^2_{\rm PT-PD}{\rm Pout}_{\rm Pri,Thr})$ and $O(\cdot)$ represents the high order terms. Besides, the second term at the right-hand side of (31) can be rewritten as

$$\begin{aligned}&\lim_{\gamma_{\rm PT}\to+\infty} \Pr(D=D_m)\Pr({\rm outage}|D=D_m)\\ &\quad= \lim_{\gamma_{\rm PT}\to+\infty} \Pr(D=D_m) \lim_{\gamma_{\rm PT}\to+\infty} \Pr({\rm outage}|D=D_m).\end{aligned} \tag{33}$$

Letting $\sigma^2_{\rm ST-PD} \to 0$, the term $\lim_{\gamma_{\rm PT}\to+\infty} \Pr(D=D_m)$ in (33) can be easily calculated from (22) as

$$\begin{aligned}\lim_{\gamma_{\rm PT}\to+\infty} \Pr(D=D_m) &= \xi^{\|\bar{D}_m\|} \prod_{j\in\bar{D}_m} \frac{\sigma^2_{{\rm PT-SR}_j}}{\sigma^2_{{\rm ST-SR}_j}}\\ &\quad\times \left(\sigma^2_{\rm ST-PD}\right)^{\|\bar{D}_m\|} + O\left(\sigma^2_{\rm ST-PD}\right)^{\|\bar{D}_m\|}.\end{aligned} \tag{34}$$

Following (23), the second term at the right-hand side of (33) can be expressed as

$$\begin{aligned}&\lim_{\gamma_{\rm PT}\to+\infty} \Pr({\rm outage}|D=D_m)\\ &\quad= \lim_{\gamma_{\rm PT}\to+\infty} \int_{-\infty}^{0} \frac{\psi}{\sigma^2_{\rm PT-SD}\Lambda\gamma_{\rm PT} + \sigma^2_{\rm ST-SD}\gamma_{\rm ST}}\\ &\qquad\times \exp\left(\frac{x}{\sigma^2_{\rm PT-SD}\Lambda\gamma_{\rm PT}}\right)dx\end{aligned} \tag{35}$$

where the parameter

$$\psi = \prod_{i \in D_m} [1 - \exp(-((\Lambda - x)/\sigma^2_{\mathrm{SR}_i-\mathrm{SD}}\gamma_{\mathrm{SR}_i}))].$$

Hence, considering $\sigma^2_{\mathrm{ST-PD}} \to 0$, (35) is derived as

$$\begin{aligned}&\lim_{\gamma_{\mathrm{PT}}\to+\infty} \Pr(\mathrm{outage}|D = D_m)\\ &= \frac{\left(\sigma^2_{\mathrm{PT-SD}}\xi\right)^{\|D_m\|+1}\|D_m\|!}{\sigma^2_{\mathrm{ST-SD}}} \prod_{i\in D_m} \frac{\vartheta_{\mathrm{SR}_i-\mathrm{PD}}}{\sigma^2_{\mathrm{SR}_i-\mathrm{SD}}} \cdot \left(\sigma^2_{\mathrm{ST-PD}}\right)^{\|D_m\|+1}\\ &\quad + O\left(\sigma^2_{\mathrm{ST-PD}}\right)^{\|D_m\|+1} \end{aligned} \tag{36}$$

where $\vartheta_{\mathrm{SR}_i-\mathrm{PD}} = \sigma^2_{\mathrm{SR}_i-\mathrm{PD}}/\sigma^2_{\mathrm{ST-PD}}$ is associated with the link quality only. Substituting (34) and (36) into (33) yields

$$\begin{aligned}&\lim_{\gamma_{\mathrm{PT}}\to+\infty} \Pr(D = D_m)\Pr(\mathrm{outage}|D = D_m)\\ &= \frac{\left(\sigma^2_{\mathrm{PT-SD}}\right)^{\|D_m\|+1}\xi^{M+1}\|D_m\|!}{\sigma^2_{\mathrm{ST-SD}}}\\ &\quad\times \prod_{i\in D_m} \frac{\vartheta_{\mathrm{SR}_i-\mathrm{PD}}}{\sigma^2_{\mathrm{SR}_i-\mathrm{SD}}} \prod_{j\in \bar{D}_m} \frac{\sigma^2_{\mathrm{PT-SR}_j}}{\sigma^2_{\mathrm{ST-SR}_j}} \cdot \left(\sigma^2_{\mathrm{ST-PD}}\right)^{M+1}\\ &\quad + O\left(\sigma^2_{\mathrm{ST-PD}}\right)^{M+1}. \end{aligned} \tag{37}$$

As shown in (32) and (37), each term in (31) behaves as $(\sigma^2_{\mathrm{ST-PD}})^{M+1}$, thus $\mathrm{Pout}_{\mathrm{multi,floor}}$ also behaves as $(\sigma^2_{\mathrm{ST-PD}})^{M+1}$, i.e., the secondary outage probability floor decreases in $M+1$ power of the interference gain. Substituting (32) and (37) into (30) yields

$$d_{\mathrm{multi}} = M + 1. \tag{38}$$

To illustrate the diversity gain analysis, we plot (28) and (31) as a function of the transmit SNR γ_{PT} and the interference level $1/\sigma^2_{\mathrm{ST-PD}}$. Fig. 4 shows that, in high SNR and low interference level regions, the diversity order curves approach to the corresponding exact outage probability results.

V. Conclusion

This correspondence demonstrated 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, and derived an exact closed-form expression of the secondary outage probability under the constraint of satisfying a required primary outage probability. Furthermore, we have generalized the traditional definition of the diversity gain and shown that the full diversity order is achieved by the proposed adaptive cooperation scheme.

Appendix A
Calculation of (23)

Substituting $\mathrm{SNR}_{\mathrm{SD}}(D = D_m)$ from (15) into (23) gives

$$\Pr(\mathrm{outage}|D=D_m) = \Pr\left\{\max_{i\in D_m} \gamma_{\mathrm{SR}_i}|h_{\mathrm{SR}_i-\mathrm{SD}}(k)|^2 < \Lambda - x\right\} \tag{A1}$$

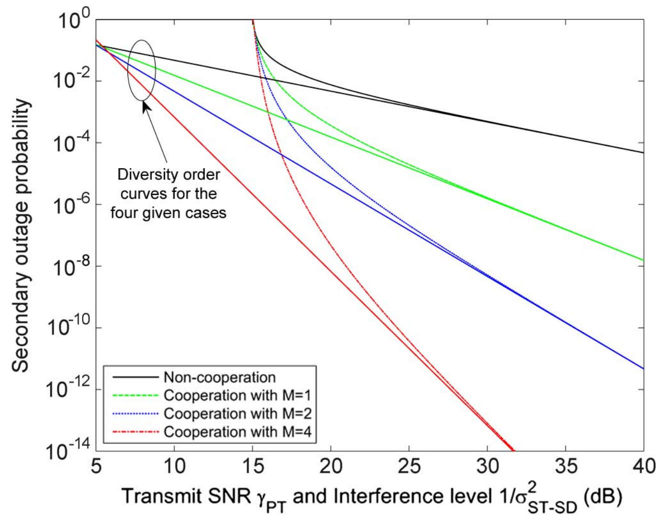

Fig. 4. Illustration of the diversity gain achieved by the non-cooperation and the adaptive cooperation schemes with a guaranteed primary outage probability threshold $\mathrm{Pout}_{\mathrm{Pri,Thr}} = 0.01$, primary data rate $R_p = 0.4$ bits/s/Hz, secondary data rate $R_s = 0.2$ bits/s/Hz, $\sigma^2_{\mathrm{PT-PD}} = \sigma^2_{\mathrm{ST-SD}} = \sigma^2_{\mathrm{ST-SR}_i} = \sigma^2_{\mathrm{SR}_i-\mathrm{SD}} = 1$, $\sigma^2_{\mathrm{PT-SD}} = \sigma^2_{\mathrm{PT-SR}_i} = 0.1$ and $\vartheta_{\mathrm{SR}_i-\mathrm{PD}} = 1$.

where $\gamma_{\mathrm{SR}_i} = P_{\mathrm{SR}_i}/N_0$, $\Lambda = 2^{2R_s} - 1$ and $x = \gamma_{\mathrm{ST}}|h_{\mathrm{ST-SD}}(k)|^2 - \Lambda\gamma_{\mathrm{PT}}|h_{\mathrm{PT-SD}}(k)|^2$. Notice that RVs $|h_{\mathrm{ST-SD}}(k)|^2$ and $|h_{\mathrm{PT-SD}}(k)|^2$ follow exponential distribution with the parameters $1/\sigma^2_{\mathrm{ST-SD}}$ and $1/\sigma^2_{\mathrm{PT-SD}}$, respectively. Hence, the probability density function of RV x can be given by

$$f(x) = \begin{cases} \frac{1}{\sigma^2_{\mathrm{ST-SD}}\gamma_{\mathrm{ST}} + \sigma^2_{\mathrm{PT-SD}}\Lambda\gamma_{\mathrm{PT}}} \exp\left(-\frac{x}{\sigma^2_{\mathrm{ST-SD}}\gamma_{\mathrm{ST}}}\right), & x \ge 0\\ \frac{1}{\sigma^2_{\mathrm{PT-SD}}\Lambda\gamma_{\mathrm{PT}} + \sigma^2_{\mathrm{ST-SD}}\gamma_{\mathrm{ST}}} \exp\left(\frac{x}{\sigma^2_{\mathrm{PT-SD}}\Lambda\gamma_{\mathrm{PT}}}\right), & x < 0. \end{cases} \tag{A2}$$

Thus, (A1) can be calculated as

$$\begin{aligned}&\Pr(\mathrm{outage}|D = D_m)\\ &= \int_{-\infty}^{\Lambda} \prod_{i\in D_m} \Pr\left[\gamma_{\mathrm{SR}_i}|h_{\mathrm{SR}_i-\mathrm{SD}}(k)|^2 < \Lambda - x\right] f(x)dx\\ &= \mathrm{A}_m + \mathrm{B}_m \end{aligned} \tag{A3}$$

where the terms A_m and B_m are given by

$$\mathrm{A}_m = \int_{-\infty}^{0} \frac{\psi}{\sigma^2_{\mathrm{PT-SD}}\Lambda\gamma_{\mathrm{PT}} + \sigma^2_{\mathrm{ST-SD}}\gamma_{\mathrm{ST}}} \exp\left(\frac{x}{\sigma^2_{\mathrm{PT-SD}}\Lambda\gamma_{\mathrm{PT}}}\right) dx \tag{A4}$$

and

$$\mathrm{B}_m = \int_{0}^{\Lambda} \frac{\psi}{\sigma^2_{\mathrm{ST-SD}}\gamma_{\mathrm{ST}} + \sigma^2_{\mathrm{PT-SD}}\Lambda\gamma_{\mathrm{PT}}} \exp\left(-\frac{x}{\sigma^2_{\mathrm{ST-SD}}\gamma_{\mathrm{ST}}}\right) dx \tag{A5}$$

wherein the parameter ψ is given by

$$\psi = \prod_{i\in D_m}\left[1-\exp\left(-\frac{\Lambda - x}{\sigma^2_{\mathrm{SR}_i-\mathrm{SD}}\gamma_{\mathrm{SR}_i}}\right)\right] = 1 + \sum_{n=1}^{2^{\|D_m\|}-1}(-1)^{\|S_m(n)\|}\exp\left(-\sum_{i\in S_m(n)}\frac{\Lambda - x}{\sigma^2_{\mathrm{SR}_i-\mathrm{SD}}\gamma_{\mathrm{SR}_i}}\right) \tag{A6}$$

where $|D_m|$ is the number of the elements of the decoding set D_m and $S_m(n)$ is the nth non-empty subcollection of the elements of D_m. Note that we have used the binomial expansion to obtain the second equation in (A6). Substituting ψ from (A6) into the term A_m and solving the integral, we have

$$\mathrm{A}_m = \Gamma + \sum_{n=1}^{2^{\|D_m\|-1}}\frac{(-1)^{\|S_m(n)\|}\Gamma}{1+\sigma^2_{\mathrm{PT-SD}}\gamma_{\mathrm{PT}}\Psi_{S_m(n)}}\exp\left(-\Psi_{S_m(n)}\right) \tag{A7}$$

where $\Gamma = \sigma^2_{\mathrm{PT-SD}}\Lambda\gamma_{\mathrm{PT}}/(\sigma^2_{\mathrm{PT-SD}}\Lambda\gamma_{\mathrm{PT}} + \sigma^2_{\mathrm{ST-SD}}\gamma_{\mathrm{ST}})$ and $\Psi_{S_m(n)} = \sum_{i\in S_m(n)}(\Lambda/\sigma^2_{\mathrm{SR}_i-\mathrm{SD}}\gamma_{\mathrm{SR}_i})$. Similarly, substituting ψ from (A6) into the term B_m, we can obtain

$$\mathrm{B}_m = (1-\Gamma)\left[1-\exp\left(-\frac{\Lambda}{\sigma^2_{\mathrm{ST-SD}}\gamma_{\mathrm{ST}}}\right) + \sum_{n=1}^{2^{\|D_m\|}-1}(-1)^{\|S_m(n)\|}\Phi_{S_m(n)}\right] \tag{A8}$$

where the parameter $\Phi_{S_m(n)}$ is calculated as (27).

Acknowledgment

The authors are grateful to the anonymous reviewers for their valuable comments and constructive suggestions that have indeed helped improve this correspondence significantly.

References

[1] S. Haykin, "Cognitive radio: Brain-empowered wireless communications," *IEEE J. Sel. Areas Commun.*, vol. 23, no. 2, pp. 201–220, 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, 2007.
[3] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062–3080, 2004.
[4] T. E. Hunter, S. Sanayei, and A. Nosratinia, "Outage analysis of coded cooperation," *IEEE Trans. Inf. Theory*, vol. 52, no. 2, pp. 375–391, Feb. 2006.
[5] Y. Zou, B. Zheng, and J. Zhu, "Outage analysis of opportunistic cooperation over Rayleigh fading channels," *IEEE Trans. Wireless Commun.*, vol. 8, no. 6, pp. 3077–3085, Jun. 2009.
[6] Y. Zou, B. Zheng, and W.-P. Zhu, "An opportunistic cooperation scheme and its BER analysis," *IEEE Trans. Wireless Commun.*, vol. 8, no. 9, pp. 4492–4497, Sep. 2009.
[7] 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.
[8] E. Beres and R. S. Adve, "Selection cooperation in multi-source cooperative networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 1, pp. 118–127, Jan. 2008.
[9] 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.
[10] G. Ganesan and Y. G. Li, "Cooperative spectrum sensing in cognitive radio-part I: Two user networks," *IEEE Trans. Wireless Commun.*, vol. 6, no. 6, pp. 2204–2213, 2007.
[11] Q. Zhi, S. Cui, and A. H. Sayed, "Optimal linear cooperation for spectrum sensing in cognitive radio networks," *IEEE J. Sel. Topics Signal Process.*, vol. 2, no. 1, pp. 28–40, Feb. 2008.
[12] O. Simeone, Y. Bar-Ness, and U. Spagnolini, "Stable throughput of cognitive radios with and without relaying capability," *IEEE Trans. Commun.*, vol. 55, no. 12, pp. 2351–2360, 2007.
[13] O. Simeone, J. Gambini, Y. Bar-Ness, and U. Spagnolini, "Cooperation and cognitive radio," in *Proc. IEEE ICC 2007*, 2007, pp. 6511–6515.
[14] J. Jia, J. Zhang, and Q. Zhang, "Cooperative relay for cognitive radio networks," in *Proc. IEEE INFOCOM 2009*, 2009, pp. 2304–2312.
[15] Q. Zhang, J. Jia, and J. Zhang, "Cooperative relay to improve diversity in cognitive radio networks," *IEEE Commun. Mag.*, vol. 47, no. 2, pp. 111–117, 2009.
[16] 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.
[17] S. Kandukuri and S. Boyd, "Optimal power control in interference-limited fading wireless channels with outage-probability specifications," *IEEE Trans. Wireless Comm.*, vol. 1, no. 1, pp. 46–55, 2002.
[18] L. Zheng and D. Tse, "Diversity and multiplexing: A fundamental tradeoff in multiple antenna channels," *IEEE Trans. Inf. Theory*, vol. 49, no. 5, pp. 1073–1096, May 2003.
[19] Y. Zou, Y.-D. Yao, and B. Zheng, "Outage probability analysis of cognitive transmissions: Impact of spectrum sensing overhead," *IEEE Trans. Wireless Commun.*, vol. 9, no. 8, pp. 2676–2688, Aug. 2010.