Zhao *et al. EURASIP Journal on Advances in Signal Processing* 2014, **2014**:34
http://asp.eurasipjournals.com/content/2014/1/34

EURASIP Journal on
Advances in Signal Processing
a SpringerOpen Journal

RESEARCH Open Access

Balancing outage performance of primary user and secondary user by relay-assisted primary transmission

Feng Zhao[1*], Xiangqi Sun[1], Hongbin Chen[1*] and Rongfang Bie[2]

Abstract

In this paper, a cooperative transmission protocol for cognitive radio systems is proposed. In this protocol, the primary system comprises a transmitter (PT), a receiver (PR), and a decode-and-forward relay (Relay), while the secondary system comprises a transmitter (ST) and a receiver (SR). Both the ST and the Relay assist the transmissions of the primary users together. The outage probabilities of the primary system and the secondary system are analyzed and verified through simulations. In order to decrease outage probability of the secondary system, power allocation is performed at the ST. However, it will lead to deterioration of outage performance of the primary system. In order to guarantee outage performance of the primary system, a Relay is employed. Compared with two existing protocols, one without cooperation and the other with cooperation of the secondary system only, the proposed protocol is able to better balance outage performances of the primary system and the secondary system.

Keywords: Cognitive radio; Decode-and-forward relaying; Outage probability; Power allocation; Relay network; Spectrum sharing

1. Introduction

With the fast development of the telecommunications industry, wireless spectrum resources are becoming increasingly scarce. Because wireless spectrum resources are limited, improving spectral efficiency and allocating the spectrum resources efficiently become the ways to solve the problem. There are two kinds of users demanding spectrum with different priorities, which are licensed users and cognitive users. Licensed users, also called primary users, have a portion of licensed spectrum to transmit signals. However, cognitive users, known as secondary users, do not own licensed spectrum. As an effective approach to solve the problem of spectrum shortage, spectrum sharing [1], which allows a portion of secondary users to access the spectrum of primary users without harmful interference, was proposed to realize spectrum reuse. Compared with licensed spectrum, unlicensed spectrum is much less. Under these circumstances, cognitive radio [2] was proposed to improve the utilization of licensed spectrum.

Cognitive radio is an intelligent technology in spectrum sharing. In cognitive radio, secondary users are allowed to access the licensed spectrum on the condition that secondary users protect the transmissions of primary users to achieve spectrum sharing. In earlier works, the authors focused on some characteristics of a simple spectrum sharing protocol, such as achievable rate and outage performance, where the system consists of a primary and a secondary transmitter-receiver pairs [3-7]. In [6], the primary system transmitted the signal with the cooperation of the secondary system, and the outage performance of the primary system was improved obviously. A similar protocol with multiple antennas was considered in [8], where the achievable rate and bit error rate for arbitrary signal-to-noise ratio were analyzed. A protocol with selection of secondary users was considered in [9], where the outage probabilities of primary and secondary systems decrease as the number of secondary transmitters increases. Cooperative relaying technology was introduced into cognitive radio networks in order to enhance network capacity, scalability, and reliability of end-to-end communications. Though the performance of primary system is improved, the performance of secondary

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* Correspondence: zhaofeng@guet.edu.cn; chbscut@163.com
[1]Key Laboratory of Cognitive Radio and Information Processing, Guilin University of Electronic Technology, Ministry of Education, Guilin 541004, China
Full list of author information is available at the end of the article

system may not be satisfied. In [10-13], the authors considered a protocol, where an intermediate relay cooperated with the communications between the secondary users, and they have considered the constraints on the average received interference at the primary users. The application of cooperative relays for secondary transmissions with the primary quality of service (QoS) constraint was considered in [14]. In [15,16], the primary and secondary systems' outage performances and system capacities were studied with the same system model, respectively. Under the condition of keeping the normal transmissions of primary users, the performance of secondary system was ameliorated in [17-20]. In [21], a relay-assisted scheme was studied, where the relay helped the transmissions of the secondary users, considering interference from primary users. Cooperation diversity technology is able to reduce the effects of fading on signals in wireless communications, and relay selection can improve the achievable rate and reduce the sensitivity of channels at the destination node. Some protocols based on relay selection in cognitive radio were studied. The cooperation diversity and power allocation with optimal relay selection was considered in [22-25]. In [26], the authors proposed a relay-assisted system in cognitive radio, where the secondary transmitter and a relay competed for a licensed spectrum as long as the interference it incurs was not harmful, and the cooperative diversity gain in terms of outage performance grows as the number of relays increases. Spectrum sharing protocols based on amplify-and-forward relaying in Rayleigh and Nakagami-*m* fading were studied in [27,28], and the outage performances of the protocols based on relay selection in Rayleigh and Nakagami-*m* fading were studied in [29,30], respectively. In [31], the authors proposed a power allocation protocol for statistical QoS provisioning in multi-relay decode-and-forward cognitive networks. While these studies mainly considered perfect channel state information, the protocols considering imperfect channel state information have been taken into account. The secondary users' communications may cause harmful interference to the primary users if the channel state information of interference links is imperfect. The primary and secondary systems' outage performances with imperfect channel state information were studied in [32-34].

In the literature mentioned above, it is easy to find that the performances of the primary and secondary systems have been studied separately, but little literature has synthesized both of them to strike a balance. For example, in [6], the secondary system helps the transmissions of the primary users. Though the outage probability of the primary system is reduced, the outage performance of the secondary system may not be guaranteed. Motivated by this fact, we propose a spectrum sharing protocol for a cognitive relay network. This protocol consists of a primary system and a secondary system. The primary system consists of a primary transmitter (PT), a decode-and-forward relay (Relay), and a primary receiver (PR). A secondary transmitter (ST) and a secondary receiver (SR) constitute the secondary system, which is allowed to access the licensed spectrum. In the proposed protocol, we ensure the outage probability of the primary system with the cooperation of the Relay and the secondary users. On the premise of smooth communications between the secondary users, we adjust the power allocation factor of the secondary system in order to improve the outage performance of the secondary system and maintain the outage performance of the primary system with the cooperation of the decode-and-forward relay.

The rest of this paper is organized as follows. In Section 2, a system model is introduced, where a secondary system and a relay cooperate with a primary system together. In Section 3, the transmission process of the proposed protocol is described, and the outage probabilities of the primary system and the secondary system are analyzed. Moreover, two existing protocols are reviewed for comparison. In Section 4, analytical results are verified through simulations, and effects of various parameters on outage probabilities are analyzed. Finally, some concluding remarks are made in Section 5.

2. System model

With the purpose of improving outage performances of the primary system and the secondary system, we consider a spectrum sharing system as depicted in Figure 1. The primary system comprises a PT, a PR, and a Relay. The secondary system comprises a ST and a SR. The secondary system and the Relay assist the transmissions of the primary users together. The outage performance

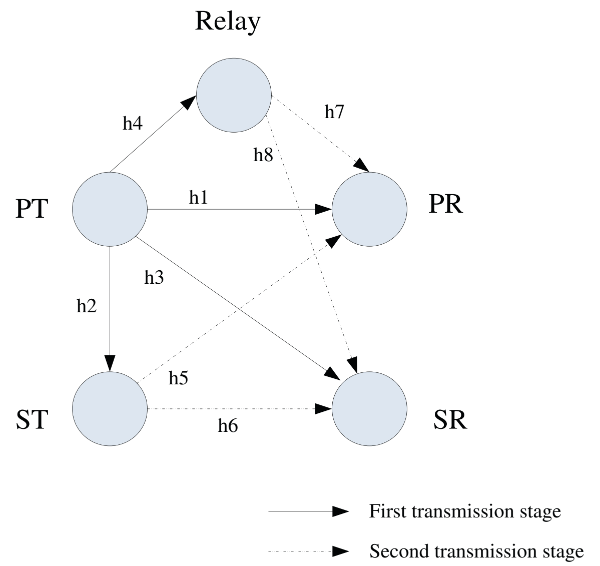

Figure 1 Spectrum sharing system model.

of the primary system benefits from the cooperation of the secondary users and the Relay. In this system, we adjust the power allocation factor at the ST in order to improve the outage performance of the secondary system, while its impact on the outage performance of the primary system will be compensated by the accommodation of the Relay.

The whole transmission process is divided into two stages. In the first transmission stage, the PT sends a primary signal to the PR, while the Relay and the ST also receive the signal. Then, the primary signal is decoded and superimposed at the ST, while the primary signal is decoded at the Relay. In the second transmission stage, a decoded signal and a weighted linear composite signal are transmitted by the Relay and the ST, respectively. The PR and the SR receive both of the signals sent from the Relay and the ST, respectively. At the PR, the primary signal is retrieved by a maximal-ratio combining (MRC) of the received signals from the two transmission stages. If the SR decodes the primary signal successfully, the primary signal will be removed as an interfering signal, and the secondary signal will be restored.

All the channels are assumed to experience Rayleigh fading [6]. The channel coefficients of the transmission links PT → PR, PT → ST, PT → SR, PT → Relay, ST → PR, ST → SR, Relay → PR, and Relay → SR are recorded by h_1, h_2, h_3, h_4, h_5, h_6, h_7, and h_8, respectively. Moreover, we assume $\mathrm{h}_i \sim CN\left(0, k_i^{-v}\right)$ [6], $i = 1, 2, 3, 4, 5, 6, 7$, and 8, and it means that h_i is a circularly symmetric complex Gaussian random variable with variance k_i^{-v}, where k_i represents the normalized distance between two nodes, and v represents the path loss exponent. That is to say, k_1, k_2, k_3, k_4, k_5, k_6, k_7, and k_8 denote the normalized distances between the PT and the PR, the PT and the ST, the PT and the SR, the PT and the Relay, the ST and the PR, the ST and the SR, the Relay and the PR, and Relay and the SR, respectively. This distance normalization is done with respect to the distance between the PT and the PR, i.e., $k_1 = 1$. Here, we also denote $\gamma_i = |h_i|^2$.

3. Signal description and outage performance analysis

3.1 Outage performance of the proposed protocol (scheme A)

We study a two-stage transmission protocol, in which the secondary users and a relay assist the transmissions of the primary users together. As shown in Figure 1, solid lines and dotted lines represent the first transmission stage and the second transmission stage, respectively.

In the first transmission stage, the PT sends the primary signal x_{p}, and the signal is received by the PR, ST, SR, and Relay. We record the received signals by the PR, ST, SR, and Relay as y_{11}, y_{21}, y_{31}, and y_{41}, respectively. They can be represented by

$$y_{a1} = \sqrt{P_{\mathrm{p}}} h_a x_{\mathrm{p}} + n_{a1}, \tag{1}$$

where $a = 1, 2, 3, 4$. Here, P_{p} is the transmission power of the primary user, h_a is the channel coefficient, and $n_{a1} \sim CN(0, \sigma^2)$ is an additive white Gaussian noise with zero mean and variance σ^2. The achievable rates between the PT and ST, the PT and SR, and the PT and Relay are denoted by R_2, R_3, and R_4, respectively. They can be written as

$$R_b = \frac{1}{2} \log_2\left(1 + \frac{P_{\mathrm{p}} \gamma_b}{\sigma^2}\right), \tag{2}$$

where $b = 2,3,4$. Here, the value $\frac{1}{2}$ is due to the fact that the whole transmission process is divided into two transmission stages. Then, both of the ST and Relay try to decode the received signal. At the ST, if decoding is successful, a weighted linear composite signal consisting of the primary signal and the secondary signal will be produced and transmitted in the second transmission stage. The regenerated signal is given by

$$\chi_{\mathrm{r}} = \sqrt{\alpha P_{\mathrm{s}}} x_{\mathrm{p}} + \sqrt{(1-\alpha) P_{\mathrm{s}}} x_{\mathrm{s}}, \tag{3}$$

Here, x_{s} denotes the secondary signal, P_{s} is transmission power of the secondary transmitter, and α is the power allocation factor. If the ST fails to decode x_{p}, it will keep silent in the second transmission stage. Likewise, if the Relay decodes x_{p} successfully, it will continue the transmissions in the next stage; otherwise, it will keep silent.

In the second transmission stage, x_{r} is transmitted by the ST and received by the PR and the SR. x_{p} is transmitted by the Relay and received by both of the PR and the SR. We represent the signal sent from the ST and received by the PR as y_{12}, which is given by

$$\begin{aligned} y_{12} &= h_5 x_{\mathrm{r}} + n_{12} \\ &= \sqrt{\alpha P_{\mathrm{s}}} h_5 x_{\mathrm{p}} + \sqrt{(1-\alpha) P_{\mathrm{s}}} h_5 x_{\mathrm{s}} + n_{12} \end{aligned} \tag{4}$$

The signal sent from the Relay and received by the PR is denoted by y_{22}, which is given by

$$y_{22} = \sqrt{P_{\mathrm{r}}} h_7 x_{\mathrm{p}} + n_{22} \tag{5}$$

The signal sent from the ST and received by the SR is denoted by y_{32}, which is given by

$$\begin{aligned} y_{32} &= h_6 x_{\mathrm{r}} + n_{32} \\ &= \sqrt{\alpha P_{\mathrm{s}}} h_6 x_{\mathrm{p}} + \sqrt{(1-\alpha) P_{\mathrm{s}}} h_6 x_{\mathrm{s}} + n_{32} \end{aligned} \tag{6}$$

The signal sent from the Relay and received by the SR is denoted by y_{42}, which is given by

$$y_{42} = \sqrt{P_{\mathrm{r}}} h_8 x_{\mathrm{p}} + n_{42} \tag{7}$$

Here, P_{r} is the transmission power of the Relay, and n_{j2} ($j = 1, 2, 3, 4$) is an additive white Gaussian noise with zero mean and variance σ^2.

The transmission will be interrupted when the achievable rate is lower than the target rate. In the proposed protocol, the primary system will communicate normally in the following conditions: on one hand, if either the ST or the Relay is able to decode x_p successfully, x_p is sent through the transmission link where x_p is decoded successfully; on the other hand, if neither the ST nor the Relay decodes x_p successfully, x_p is sent through the direct link from the PT to the PR. In each condition, a MRC of the received signals is adopted to retrieve the primary signal in the second transmission stage [6]. In the following, we analyze the achievable rate for each of them.

(1) A case that the ST decodes the primary signal x_p successfully, but the Relay fails to decode it. In this case, y_{11} and y_{12} are combined with MRC at the PR. The achievable rate between the PT and the PR is calculated by

$$R_{11}^{\mathrm{MRC}} = \frac{1}{2}\log_2\left(1 + \frac{P_\mathrm{p}\gamma_1}{\sigma^2} + \frac{\alpha P_\mathrm{s}\gamma_5}{(1-\alpha)P_\mathrm{s}\gamma_5 + \sigma^2}\right) \tag{8}$$

(2) A case that both the ST and the Relay decode the primary signal successfully. Under the circumstances, y_{11}, y_{12}, and y_{22} are combined with MRC at the PR. The achievable rate between the PT and the PR is calculated by

$$R_{12}^{\mathrm{MRC}} = \frac{1}{2}\log_2\left(1 + \frac{P_\mathrm{p}\gamma_1}{\sigma^2} + \frac{\alpha P_\mathrm{s}\gamma_5}{(1-\alpha)P_\mathrm{s}\gamma_5 + \sigma^2} + \frac{P_\mathrm{r}\gamma_7}{\sigma^2}\right) \tag{9}$$

(3) A case that the Relay is able to decode the primary signal successfully, but the ST fails to do so. Similarly, MRC will be applied to combine the signals y_{11} and y_{22} at the PR. The achievable rate between the PT and the PR is calculated by

$$R_{13}^{\mathrm{MRC}} = \frac{1}{2}\log_2\left(1 + \frac{P_\mathrm{p}\gamma_1}{\sigma^2} + \frac{P_\mathrm{r}\gamma_7}{\sigma^2}\right) \tag{10}$$

(4) For the latter condition, neither the ST nor the Relay decodes the primary signal successfully. The primary signal x_p is transmitted through the direct link from the PT to the PR. The achievable rate between them is given by

$$R_1 = \log_2\left(1 + \frac{P_\mathrm{p}\gamma_1}{\sigma^2}\right) \tag{11}$$

So, the outage probability of the primary system with target rate R_pt is calculated by

$$\begin{aligned}P_{\mathrm{out}}^{\mathrm{p,A}} = {} & 1-P_\mathrm{r}\{R_2 > R_\mathrm{pt}\}P_\mathrm{r}\{R_4 < R_\mathrm{pt}\}P_\mathrm{r}\{R_{11}^{\mathrm{MRC}} > R_\mathrm{pt}\}\\ & -P_\mathrm{r}\{R_2 > R_\mathrm{pt}\}P_\mathrm{r}\{R_4 > R_\mathrm{pt}\}P_\mathrm{r}\{R_{12}^{\mathrm{MRC}} > R_\mathrm{pt}\},\\ & -P_\mathrm{r}\{R_2 < R_\mathrm{pt}\}P_\mathrm{r}\{R_4 > R_\mathrm{pt}\}P_\mathrm{r}\{R_{13}^{\mathrm{MRC}} > R_\mathrm{pt}\}\\ & -P_\mathrm{r}\{R_2 < R_\mathrm{pt}\}P_\mathrm{r}\{R_4 < R_\mathrm{pt}\}P_\mathrm{r}\left\{\frac{1}{2}R_1 > R_\mathrm{pt}\right\}\end{aligned} \tag{12}$$

where the factor $\frac{1}{2}$ is due to the fact that the whole transmission process consists of two transmission stages. Since $\gamma_1 \sim \varepsilon(1)$, and $\gamma_i \sim \varepsilon(k_i^\nu)$ $(i = 2,3,4,5,6,7)$, which means an exponential distributed random variable with mean $\frac{1}{k_i^\nu}$, we obtain

$$P_\mathrm{r}\{R_2 > R_\mathrm{pt}\} = P_\mathrm{r}\left\{\gamma_2 > \frac{\sigma^2}{P_\mathrm{p}}\rho_1\right\} = \exp\left(-k_2^\nu\frac{\sigma^2}{P_\mathrm{p}}\rho_1\right) \tag{13}$$

$$P_\mathrm{r}\left\{\frac{1}{2}R_1 > R_\mathrm{pt}\right\} = P_\mathrm{r}\left\{\gamma_1 > \frac{\sigma^2}{P_\mathrm{p}}\rho_1\right\} = \exp\left(-\frac{\sigma^2}{P_\mathrm{p}}\rho_1\right) \tag{14}$$

$$P_\mathrm{r}\{R_4 > R_\mathrm{pt}\} = P_\mathrm{r}\left\{\gamma_4 > \frac{\sigma^2}{P_\mathrm{p}}\rho_1\right\} = \exp\left(-k_4^\nu\frac{\sigma^2}{P_\mathrm{p}}\rho_1\right) \tag{15}$$

Here, $\rho_1 = 2^{2R_\mathrm{pt}}-1$. Assuming that $P_\mathrm{s} >> \sigma^2$, we have

$$\begin{aligned}P_\mathrm{r}\{R_{11}^{\mathrm{MRC}} > R_\mathrm{pt}\} &= P_\mathrm{r}\left\{\frac{1}{2}\log_2\left(1 + \frac{P_\mathrm{p}\gamma_1}{\sigma^2} + \frac{\alpha P_\mathrm{s}\gamma_5}{(1-\alpha)P_\mathrm{s}\gamma_5 + \sigma^2}\right) > R_\mathrm{pt}\right\}\\ &\approx P_\mathrm{r}\left\{\frac{P_\mathrm{p}\gamma_1}{\sigma^2} + \frac{\alpha}{1-\alpha} > \rho_1\right\} = P_\mathrm{r}\left\{\gamma_1 > \frac{\sigma^2}{P_\mathrm{p}}\left(\rho_1 - \frac{\alpha}{1-\alpha}\right)\right\}\\ &= \begin{cases}\exp\left(-\frac{\sigma^2}{P_\mathrm{p}}\left(\rho_1 - \frac{\alpha}{1-\alpha}\right)\right) & 0 \le \alpha < \alpha^*\\ 1 & \alpha^* \le \alpha < 1,\end{cases}\end{aligned} \tag{16}$$

where $\alpha^* = \frac{\rho_1}{1+\rho_1}$. Similarly, we have

$$\begin{aligned}P_\mathrm{r}\{R_{12}^{\mathrm{MRC}} > R_\mathrm{pt}\} &= P_\mathrm{r}\left\{\frac{1}{2}\log_2\left(1 + \frac{P_\mathrm{p}\gamma_1}{\sigma^2} + \frac{\alpha P_\mathrm{s}\gamma_5}{(1-\alpha)P_\mathrm{s}\gamma_5 + \sigma^2} + \frac{P_\mathrm{r}\gamma_7}{\sigma^2}\right) > R_\mathrm{pt}\right\}\\ &\approx P_\mathrm{r}\left\{P_\mathrm{p}\gamma_1 + P_\mathrm{r}\gamma_7 > \sigma^2\left(\rho_1 - \frac{\alpha}{1-\alpha}\right)\right\} = \begin{cases}P_1 & 0 \le \alpha < \alpha^*\\ 1 & \alpha^* \le \alpha < 1,\end{cases}\end{aligned} \tag{17}$$

where $P_1 = \exp\left(-\frac{\sigma^2\left(\rho_1 - \frac{\alpha}{1-\alpha}\right)}{P_\mathrm{p}}\right) - \left(-1 + k_7^\nu\frac{P_\mathrm{p}}{P_\mathrm{r}}\right)^{-1}\exp\left(-k_7^\nu\frac{\sigma^2\left(\rho_1 - \frac{\alpha}{1-\alpha}\right)}{P_\mathrm{r}}\right)\left(1 - \exp\left(\left(-1 + k_7^\nu\frac{P_\mathrm{p}}{P_\mathrm{r}}\right)\frac{\sigma^2\left(\rho_1 - \frac{\alpha}{1-\alpha}\right)}{P_\mathrm{p}}\right)\right)$, and

$$\begin{aligned}P_\mathrm{r}\{R_{13} > R_\mathrm{pt}\} &= P_\mathrm{r}\left\{\frac{1}{2}\log_2\left(1 + \frac{P_\mathrm{p}\gamma_1}{\sigma^2} + \frac{P_\mathrm{r}\gamma_7}{\sigma^2}\right) > R_\mathrm{pt}\right\}\\ &= P_\mathrm{r}\{P_\mathrm{p}\gamma_1 + P_\mathrm{r}\gamma_7 > \rho_1\sigma^2\} = 1-P_\mathrm{r}\{P_\mathrm{p}\gamma_1 + P_r\gamma_7 \le \rho_1\sigma^2\}\\ &= \exp\left(-\frac{\rho_1\sigma^2}{P_\mathrm{p}}\right) + \exp\left(-\frac{\rho_1\sigma^2}{P_\mathrm{r}}k_7^\nu\right)\left(-1 + k_7^\nu\frac{P_\mathrm{p}}{P_\mathrm{r}}\right)^{-1}\\ &\quad\left(\exp\left(\left(-1 + k_7^\nu\frac{P_\mathrm{p}}{P_\mathrm{r}}\right)\frac{\rho_1\sigma^2}{P_\mathrm{p}}\right)-1\right)\end{aligned} \tag{18}$$

Substituting (13) to (18) into (12), we have

$$P_{\mathrm{out}}^{\mathrm{p,A}} = \begin{cases}P_{\mathrm{out}}^{\mathrm{p,1}} & 0 \le \alpha < \alpha*\\ P_{\mathrm{out}}^{\mathrm{p,2}} & \alpha* \le \alpha \le 1\end{cases}\quad, \tag{19}$$

where

$$P_{\text{out}}^{\text{p},1} = 1- \exp\left(-k_2^\nu \frac{\sigma^2}{P_\text{p}}\rho_1\right)\left(1- \exp\left(-k_4^\nu \frac{\sigma^2}{P_\text{p}}\rho_1\right)\right)\exp\left(-\frac{\sigma^2}{P_\text{p}}\left(\rho_1 - \frac{\alpha}{1-\alpha}\right)\right) - \exp\left(-k_2^\nu \frac{\sigma^2}{P_\text{p}}\rho_1\right)\exp\left(-k_4^\nu \frac{\sigma^2}{P_\text{p}}\rho_1\right)\left(\begin{array}{l}\exp\left(-\frac{\sigma^2\left(\rho_1 - \frac{\alpha}{1-\alpha}\right)}{P_\text{p}}\right) - \left(-1 + k_7^\nu \frac{P_\text{p}}{P_\text{r}}\right)^{-1}\exp\left(-k_7^\nu \frac{\sigma^2\left(\rho_1 - \frac{\alpha}{1-\alpha}\right)}{P_\text{r}}\right)\\ \left(1- \exp\left(\left(-1 + k_7^\nu \frac{P_\text{p}}{P_\text{r}}\right)\frac{\sigma^2\left(\rho_1 - \frac{\alpha}{1-\alpha}\right)}{P_\text{p}}\right)\right)\end{array}\right),$$

$$-\left(1- \exp\left(-k_2^\nu \frac{\sigma^2}{P_\text{p}}\rho_1\right)\right)\exp\left(-k_4^\nu \frac{\sigma^2}{P_\text{p}}\rho_1\right)\left(\begin{array}{l}\exp\left(-\frac{\rho_1\sigma^2}{P_\text{p}}\right) + \exp\left(-\frac{\rho_1\sigma^2}{P_\text{r}}k_7^\nu\right)\left(-1 + k_7^\nu \frac{P_\text{p}}{P_\text{r}}\right)^{-1}\\ \left(\exp\left(\left(-1 + k_7^\nu \frac{P_\text{p}}{P_\text{r}}\right)\frac{\rho_1\sigma^2}{P_\text{p}}\right) - 1\right)\end{array}\right) - \left(1- \exp\left(-k_2^\nu \frac{\sigma^2}{P_\text{p}}\rho_1\right)\right)\left(1- \exp\left(-k_4^\nu \frac{\sigma^2}{P_\text{p}}\rho_1\right)\right)\exp\left(-\frac{\sigma^2}{P_\text{p}}\rho_1\right)$$

and

$$\begin{aligned}P_{\text{out}}^{\text{p},2} = 1- &\exp\left(-k_2^\nu \frac{\sigma^2}{P_\text{p}}\rho_1\right)\left(1- \exp\left(-k_4^\nu \frac{\sigma^2}{P_\text{p}}\rho_1\right)\right) - \exp\left(-k_2^\nu \frac{\sigma^2}{P_\text{p}}\rho_1\right)\\ &\exp\left(-k_4^\nu \frac{\sigma^2}{P_\text{p}}\rho_1\right) \quad -\left(1- \exp\left(-k_2^\nu \frac{\sigma^2}{P_\text{p}}\rho_1\right)\right)\exp\left(-k_4^\nu \frac{\sigma^2}{P_\text{p}}\rho_1\right)\\ &\left(\exp\left(-\frac{\rho_1\sigma^2}{P_\text{p}}\right) + \left(-1 + k_7^\nu \frac{P_\text{p}}{P_\text{r}}\right)^{-1}\left(\exp\left(-\frac{\rho_1\sigma^2}{P_\text{p}}\right) - \exp\left(-\frac{\rho_1\sigma^2}{P_\text{p}}k_7^\nu\right)\right)\right).\\ &-\left(1- \exp\left(-k_2^\nu \frac{\sigma^2}{P_\text{p}}\rho_1\right)\right)\left(1- \exp\left(-k_4^\nu \frac{\sigma^2}{P_\text{p}}\rho_1\right)\right)\exp\left(-\frac{\sigma^2}{P_\text{p}}\rho_1\right)\end{aligned}$$

The secondary signal is transmitted on the condition that both the ST and the SR decode the primary signal x_p successfully. In this case, the primary signal will be removed as an interference at the SR [6]. Therefore, the components $\sqrt{\alpha P_\text{s}}h_6 x_\text{p}$ and $\sqrt{P_\text{r}}h_8 x_\text{p}$ can be removed from (6) and (7), respectively. Thus, we have $\hat{y}_{32} = \sqrt{(1-\alpha)P_\text{s}}h_6 x_\text{s} + n_{32}$ and $\hat{y}_{42} = n_{42}$. So, the secondary signals will be transmitted in two cases, and they are as follows.

First, the Relay fails to decode x_p, and it will keep silent in the second transmission stage. The achievable rate between the ST and the SR is calculated by

$$R_6 = \frac{1}{2}\log_2\left(1 + \frac{(1-\alpha)P_\text{s}\gamma_6}{\sigma^2}\right) \tag{20}$$

Second, the Relay succeeds to decode x_p, and it results in noise at the SR. Under the circumstances, the received signal at the SR is $y_{52} = \sqrt{(1-\alpha)P_\text{s}}h_6 x_\text{s} + n_{32} + n_{42}$. So, the achievable rate between the ST and the SR is calculated by

$$R_{21} = \frac{1}{2}\log_2\left(\frac{(1-\alpha)P_\text{s}\gamma_6}{2\sigma^2}\right) \tag{21}$$

So, we have

$$\begin{aligned}P_{\text{out}}^{\text{s,A}} &= 1 - P_\text{r}\{R_2 > R_\text{pt}\}P_\text{r}\{R_3 > R_\text{pt}\}P_\text{r}\{R_4 < R_\text{pt}\}P_\text{r}\{R_6 > R_\text{st}\}\\ &\quad - P_\text{r}\{R_2 > R_\text{pt}\}P_\text{r}\{R_3 > R_\text{pt}\}P_\text{r}\{R_4 > R_\text{pt}\}P_\text{r}\{R_{21} > R_\text{st}\}\\ &= 1- \exp\left(-\left(k_2^\nu + k_3^\nu + k_4^\nu\right)\frac{\sigma^2}{P_\text{p}}\rho_1 - k_6^\nu \frac{2\sigma^2}{(1-\alpha)P_\text{s}}\rho_3\right)\\ &\quad - \exp\left(-\left(k_2^\nu + k_3^\nu\right)\frac{\sigma^2}{P_\text{p}}\rho_1 - k_6^\nu \frac{\sigma^2}{(1-\alpha)P_\text{s}}\rho_3\right)\left(1- \exp\left(-k_4^\nu \frac{\sigma^2}{P_\text{p}}\rho_1\right)\right),\end{aligned} \tag{22}$$

where $\rho_3 = 2^{2R_\text{st}} - 1$.

3.2 Outage probability of the scheme without cooperation (scheme B)

The scheme without cooperation is the protocol without the secondary system and the Relay. It means that there is only a primary transmitter-receiver pair (PT-PR) in the system. In this system, the primary signal is transmitted only through the direct link from the PT to the PR. So, we obtain the outage probability of the primary system as follows:

$$P_{\text{out}}^0 = P_\text{r}\{R_1 < R_\text{pt}\} = 1- \exp\left(-\frac{\sigma^2}{P_\text{p}}\rho_2\right), \tag{23}$$

where $\rho_2 = 2^{R_\text{pt}} - 1$.

3.3 Outage probability of the scheme with the cooperation of the secondary system only (scheme C)

The scheme with the cooperation of the secondary system only is the protocol where the primary and secondary systems comprise a transmitter-receiver pair. In [6], this protocol has been analyzed thoroughly. The outage probability of the primary system is given by

$$P_{\text{out}}^{\text{p,C}} = \begin{cases}P_{\text{out}}^{\text{p},3} & 0 \le \alpha < \alpha^*\\ P_{\text{out}}^{\text{p},4} & \alpha^* \le \alpha \le 1,\end{cases} \tag{24}$$

where $P_{\text{out}}^{\text{p},3} = 1- \exp\left(-\frac{\sigma^2}{P_\text{p}}\left(\left(k_2^\nu + 1\right)\rho_1 - \frac{\alpha}{1-\alpha}\right)\right) - \exp\left(-\frac{\sigma^2}{P_\text{p}}\rho_1\right) + \exp\left(-\frac{\sigma^2}{P_\text{p}}\rho_1\left(k_2^\nu + 1\right)\right)$, and $P_{\text{out}}^{\text{p},4} = 1- \exp\left(-k_2^\nu \frac{\sigma^2}{P_\text{p}}\rho_1\right) - \exp\left(-\frac{\sigma^2}{P_\text{p}}\rho_1\right) + \exp\left(-\frac{\sigma^2}{P_\text{p}}\rho_1\left(k_2^\nu + 1\right)\right)$.

The outage probability of the secondary system is given by

$$\begin{aligned}P_{\text{out}}^{\text{s,C}} &= 1 - P_\text{r}\{R_2 > R_\text{pt}\}P_\text{r}\{R_3 > R_\text{pt}\}P_\text{r}\{R_6 > R_\text{st}\}\\ &= 1- \exp\left(-\left(\frac{\sigma^2\left(k_2^\nu + k_3^\nu\right)\rho_1}{P_\text{p}} + \frac{\sigma^2 k_6^\nu \rho_3}{P_\text{s}(1-\alpha)}\right)\right)\end{aligned} \tag{25}$$

4. Simulation results and discussions

In Section 3, we have introduced three different spectrum sharing schemes, including two kinds of cooperative transmission protocols and a protocol without cooperation. In this section, we will simulate $P_{\text{out}}^{\text{p}}$ and $P_{\text{out}}^{\text{s}}$ with the variation of α for each protocol. Most of the simulation parameters are the same as those in [6]. We set $\nu = 4$, $\frac{P_{\text{p}}}{\sigma^2} = \frac{P_{\text{s}}}{\sigma^2} = \frac{P_{\text{r}}}{\sigma^2} = 20$ dB, and $\sigma^2 = 1$. Moreover, the target rates are set as $R_{\text{pt}} = R_{\text{st}} = 2$, which are different from those in [6]. The reason is that the transmissions in the proposed scheme are able to support higher rates compared with those of the other two schemes. For ease of exposition, the topological structure is constructed like this as an example: the PT, PR, ST, SR, and Relay are collinear. In the two-dimensional plane, the PT and the PR are located at the points (0, 0) and (1, 0), respectively. The ST moves on the positive X axis. The SR is at the midpoint of the PT and the ST, and the Relay is at the midpoint of the PT and the PR. In this topology, we have $k_1 = 1$, $k_3 = \frac{1}{2}k_2$, $k_4 = \frac{1}{2}k_1$, $k_5 = |1 - k_2|$, $k_6 = \frac{1}{2}k_2$, $k_7 = \frac{1}{2}k_1$, and $k_8 = \frac{1}{2}|k_1 - k_2|$. From the expression of $P_{\text{out}}^{\text{p},1}$, it is easy to find that $\frac{\alpha}{1-\alpha}$ increases with the growth of α. Furthermore, $P_{\text{out}}^{\text{p},1}$ decreases with the growth of α in case of $0 \leq \alpha < \frac{\rho_1}{1+\rho_1}$. At the same time, we know that $P_{\text{out}}^{\text{s,A}}$ increases with the growth of α from (22). In other words, when more transmission power is allocated to assist the transmissions of the primary users at the ST, the outage performance of the primary system becomes better, whereas the outage performance of the secondary system becomes worse. In Figures 2 and 3, we plot the outage probabilities of the primary system and secondary system versus the power allocation factor when $k_2 = 0.5$, 1.2, 1.92, respectively. In the figures, lines represent theoretical results, and markers represent simulation results. Note that the theoretical results match with the simulation results very well. It is easy to find that in the proposed protocol, $P_{\text{out}}^{\text{p,A}}$ is lower than $P_{\text{out}}^{\text{o}}$, which means that the outage probability of the primary system in scheme A is much lower than that in scheme B.

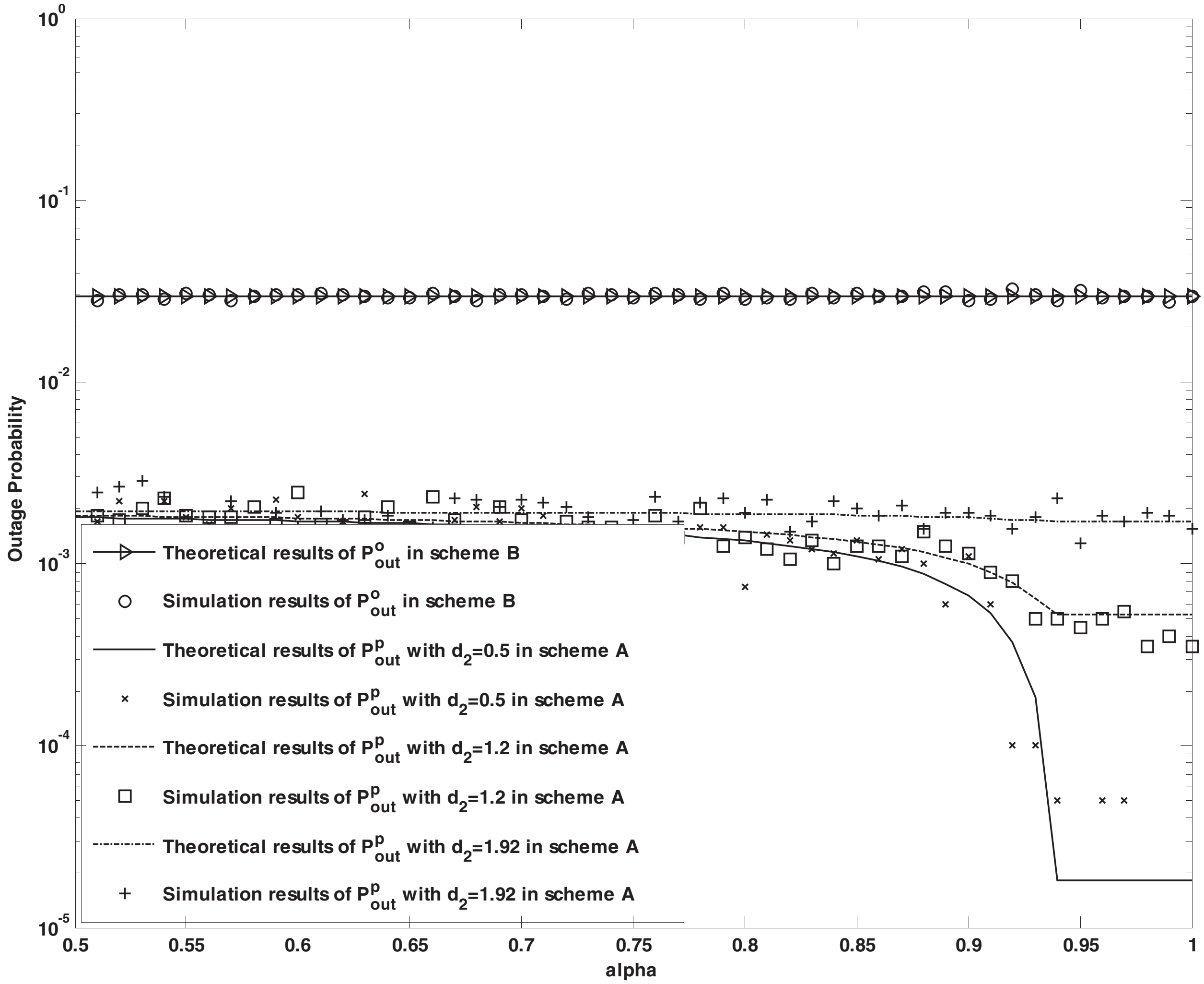

Figure 2 **Outage probability of primary system comparison between schemes A and B when $k_2 = 0.5$, $k_2 = 1.2$, and $k_2 = 1.92$.**

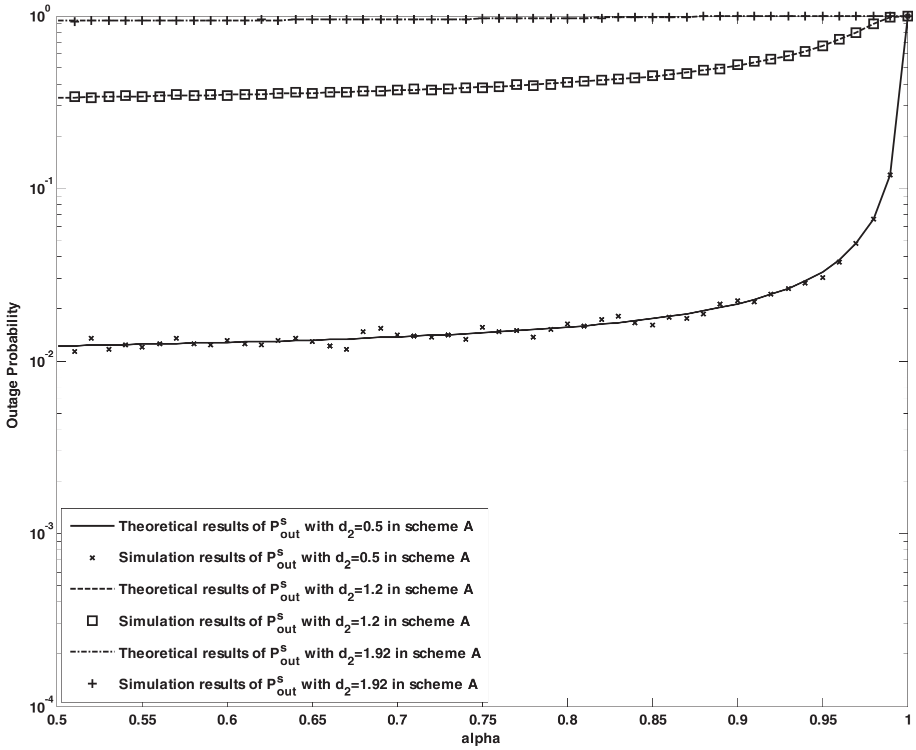

Figure 3 Outage probability of the secondary system in scheme A when $k_2 = 0.5$, $k_2 = 1.2$, and $k_2 = 1.92$.

As shown in Figures 4, 5 and 6, we compare the outage performances in schemes A and C when $k_2 = 0.5$, $k_2 = 1.2$, and $k_2 = 1.92$, respectively. In these figures, the topological structure is the same as that in Figure 2. The parameters are set as $\nu = 4$, $\frac{P_p}{\sigma^2} = \frac{P_s}{\sigma^2} = \frac{P_r}{\sigma^2} = 20$ dB, $R_{pt} = R_{st} = 2$, and $\sigma^2 = 1$. The lines represent the theoretical results, and markers represent the simulation results. Compared with scheme C, there is a decode-and-forward relay cooperating with the primary users in scheme A, so the outage performance of the primary system will be improved. Because of the interference caused by the Relay, the outage performance of the secondary system becomes a little worse. From Figures 4, 5 and 6, it is seen that with different settings of k_2, $P^{p,A}_{out}$ is less than P^{o}_{out} and far less than $P^{p,C}_{out}$ with the variation of α.

We observe that the outage probabilities of the primary system in the three schemes are low, but the outage probabilities of the secondary system are high, especially in the setting of $k_2 = 1.92$. Since $P^{p,A}_{out}$ is less than P^{o}_{out}, we are allowed to reduce the value of α in order to guarantee smooth communications between the secondary users. In other words, a small portion of transmission power of the secondary transmitter is allocated to send the primary signal. Under the circumstances, the outage performance of the primary system will degrade. Then, we try to guarantee $P^{p,A}_{out}$ by increasing the P_r. So, we will simulate the influence of P_r on P^{p}_{out}. Here, we set $k_2 = 1.92$, and $\alpha = 0.1$. The other parameters except P_r are the same as those in Figure 6, which means that the ST is far away from the PT, and a small portion of the transmission power of the ST is allocated to send the primary signal. From Figure 7, we get that $P^{p,A}_{out}$ decreases with the growth of Pr, and $P^{p,A}_{out}$ tends to be stable with the growth of P_r.

It is easy to find that both $P^{p,A}_{out}$ and P^{o}_{out} decrease with the growth of P_p from (19) and (23). From (22), we know that $P^{s,A}_{out}$ is independent from P_s and k_6 when k_6 is very small. That is to say that when the distance between the ST and the SR is short, $P^{s,A}_{out}$ is not affected by P_s or k_6, and $P^{s,A}_{out}$ converges to $1 - \exp\left(-\frac{\sigma^2\left(k_2^{\nu} + k_3^{\nu}\right)\rho_1}{P_p}\right)$. Here, the topological structure is the same as that in Figure 2, and we set $P_s = 100$, $P_r = 10$, $\sigma^2 = 10$, $\alpha = 0.5$, $R_{pt} = R_{st} = 2$, and $\nu = 4$. So, $P^{s,A}_{out}$ decreases with the growth of P_p. From Figure 8, we find that the simulation results agree with the analytical ones.

When the ST is not close to the SR, we analyze the outage probability expressions of the primary and secondary systems. For the primary system, $P^{p,A}_{out}$ is independent from P_s from (19), and $P^{s,A}_{out}$ decreases with the growth of P_s from (22). So, we build a different

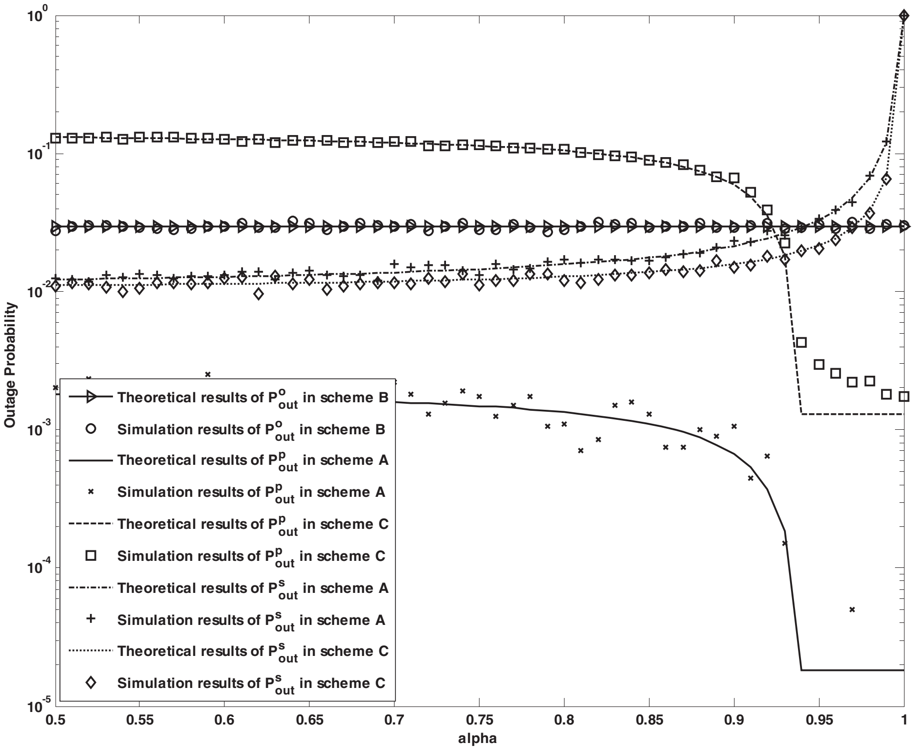

Figure 4 Outage probability comparison between schemes A and C when $k_2 = 0.5$.

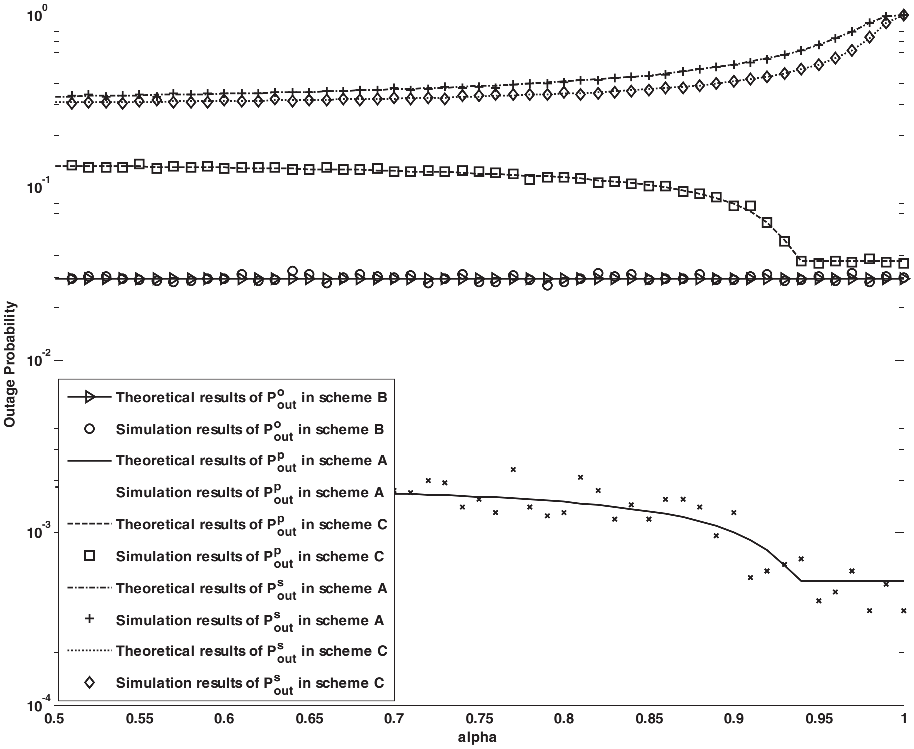

Figure 5 Outage probability comparison between schemes A and C when $k_2 = 1.2$.

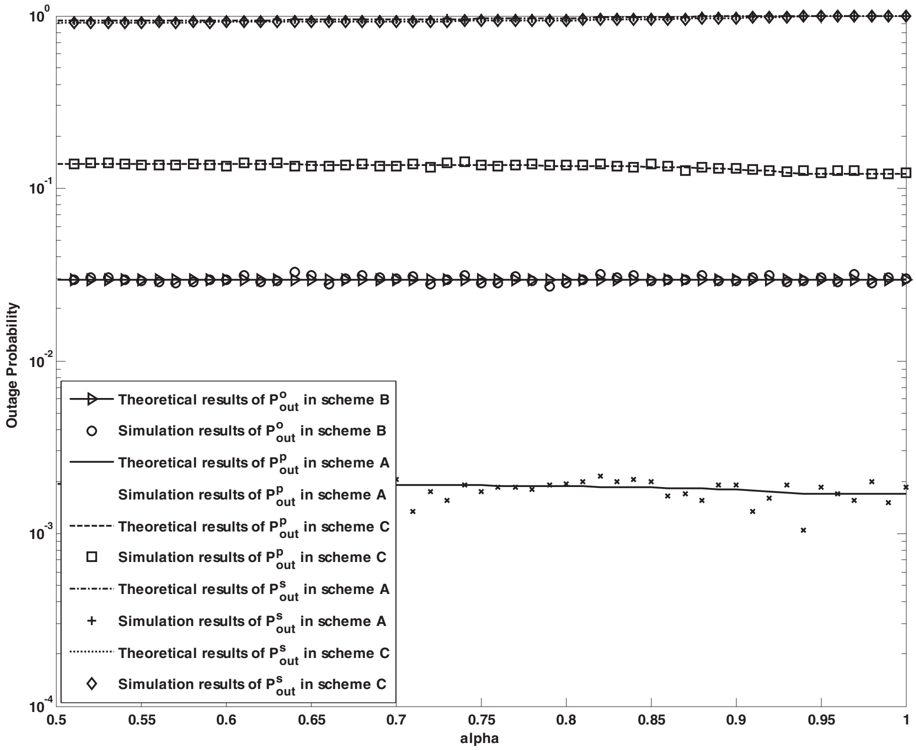

Figure 6 Outage probability comparison between schemes A and C when $k_2 = 1.92$.

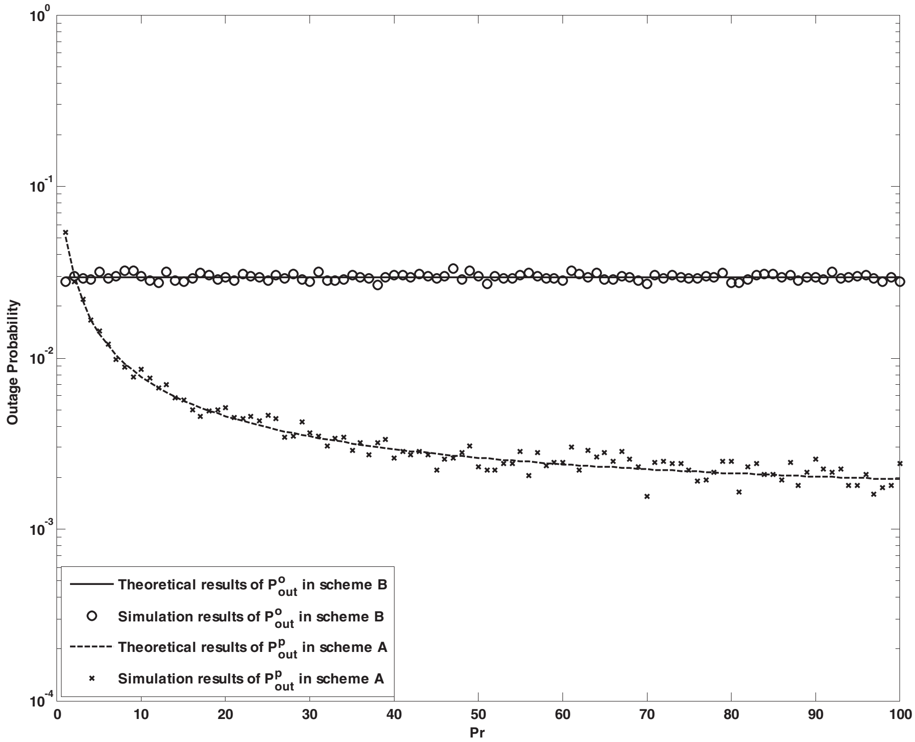

Figure 7 Outage probability of the primary system versus P_r.

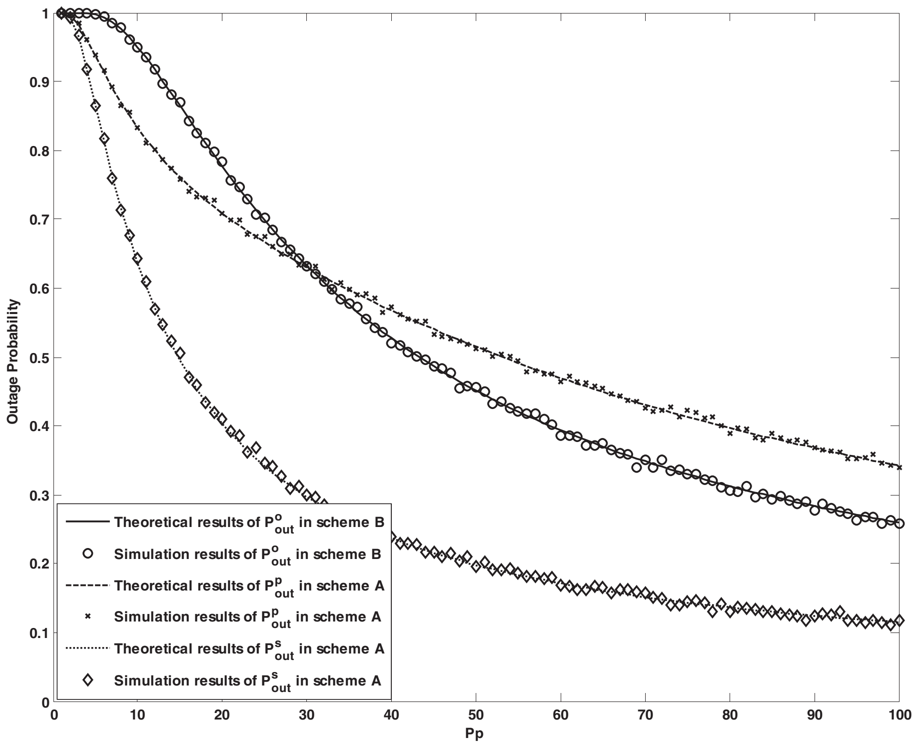

Figure 8 Outage probability versus P_p.

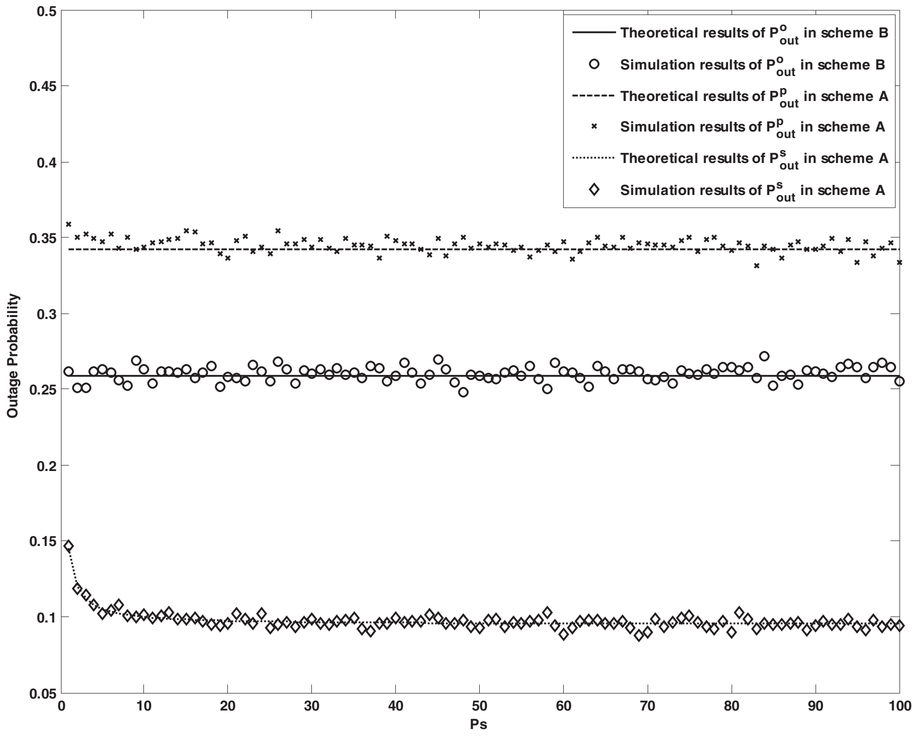

Figure 9 Outage probability versus P_s.

topological structure with the following parameters $k_2 = k_3 = k_4 = k_5 = k_6 = k_7 = k_8 = 0.5$, $P_{\mathrm{p}} = 100$, $P_{\mathrm{r}} = 10$, $\sigma^2 = 10$, $\alpha = 0.5$, $R_{\mathrm{pt}} = R_{\mathrm{st}} = 2$, and $v = 4$, which mean that the ST is far from the SR, and the signal-to-noise ratios of the transmission links are relatively low. As Figure 9 shows, the variation of $P_{\mathrm{out}}^{\mathrm{s,A}}$ coincides with the analytical results. Though the growth of P_{s} improves the outage performance of the secondary system and does not greatly affect the outage performance of the primary system, P_{s} cannot increase unlimitedly. Meanwhile, the assistance of the Relay can improve the outage performance of the primary system.

5. Conclusions

In this paper, a cooperative transmission protocol where secondary users and a relay assist the transmissions of primary users was proposed. Compared with the protocol in [6], the proposed protocol can decrease the outage probability of the secondary system while maintaining the outage performance of the primary system. More specifically, the outage performance of the secondary system is improved by the power allocation at the secondary transmitter. Meanwhile, the outage performance of the primary system is guaranteed by the accommodating a relay.

Competing interests

The authors declare that they have no competing interests.

Acknowledgements

We would like to thank the National Natural Science Foundation of China (61172055, 61162008), the Guangxi Natural Science Foundation (2011GXNSFB018072, 2013GXNSFGA019004), the Key Project of Chinese Ministry of Education (212131), the Foundation of Department of Education of Guangxi Province (201202ZD045), the Open Research Fund of Guangxi Key Laboratory of Wireless Wideband Communication & Signal Processing (12106, 12103), and the Project of the Key Laboratory of Cognitive Radio and Information Processing (Guilin University of Electronic Technology), Ministry of Education (2013ZR02).

Author details

[1]Key Laboratory of Cognitive Radio and Information Processing, Guilin University of Electronic Technology, Ministry of Education, Guilin 541004, China. [2]College of Information Science and Technology, Beijing Normal University, Beijing 100875, China.

Received: 23 December 2013 Accepted: 28 February 2014
Published: 17 March 2014

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doi:10.1186/1687-6180-2014-34
Cite this article as: Zhao *et al.*: Balancing outage performance of primary user and secondary user by relay-assisted primary transmission. *EURASIP Journal on Advances in Signal Processing* 2014 **2014**:34.