

Wireless Energy Harvesting in Cognitive AF Network With Relay Selection

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Abstract. In this paper, we propose an improved cognitive amplify-and-forward relaying model, in which the multiple secondary users can harvest energy from the primary network, assisting primary user transmission and meanwhile performing secondary transmission in a spectrum-sharing network. One secondary user having highest harvested energy among multiple secondary users will be selected as a relay to broadcast information. The outage probabilities (OP) of the primary and secondary network are investigated to evaluate the performance of network over Rayleigh fading channels. In particular, we derive the analytical expression of OP for primary and secondary network. Moreover, the closed-form expression of lower bound for OP at secondary user is obtained. Analysis results are validated by the Monte-Carlo simulation results, which show that the improved cognitive radio model and the number of relays have significant improvement in the system OP.

Introduction

Cooperative communication in cognitive radio (CR) network has been recognized as an efficient way to improve the spectrum utilization efficiency. In [1], the outage performance of cooperative cognitive amplify-and-forward (AF) relaying in spectrum-sharing networks was studied. The works in [2] presented that the secondary network can share the spectrum by assisting primary transmission and performing secondary transmission simultaneously.

Recently, energy harvesting in wireless communication networks has attracted considerable attention, since it is a key technology to prolong the lifetime of communication networks. The technology lies in the fact that radio-frequency (RF) signals can carry energy and information simultaneously [3] [4]. Therefore, nodes can harvest energy from ambient signals and process information at the same time [5]. A wireless energy harvesting protocol was proposed in [6], where the secondary network harvests energy from primary user in a cognitive spectrum sharing network, which meets the requirements of energy efficiency and spectral efficiency in a wireless network.

A practical design for simultaneous wireless information and power transfer based on dynamic power splitting mechanism was investigated in [7]. Authors in [8] proposed a relaying protocol, energy constrained relay can harvest energy from RF signals and exploit the energy to transmit the source signal to the destination. In [9], the secondary user harvesting energy from received signals acts as a relay to assist the primary transmission and share the spectrum with no need for consuming extra energy of secondary network. A relay selection protocol was proposed for decode-and-forward relaying network in [10], where one relay among multiple energy harvesting relays will be chosen to help the source transmission. An improved CR model was proposed in [11] that the secondary system can harvest energy from RF signals and share the spectrum of primary system to broadcast its own information. To be the best of our knowledge, relay selection in cognitive AF relay network with energy harvesting under overlay model has not been investigated.

Our paper considers a two-hop cognitive AF relaying networks with multiple energy harvesting secondary users. In order to enhance the quality of service of primary system and obtain the opportunity to transmit its own signal to secondary receiver, one secondary user with the highest harvested energy will be chosen as a relay to assist the primary transmission based on the relay selection protocol proposed in [10]. According to the PSR protocol, the selected secondary user harvests energy from part of its received primary signals and exploits the harvested energy to

broadcast the primary and secondary signals. For performance evaluation, we derive the exact expression for the outage probability (OP) of the primary and secondary system in a CR network over Rayleigh fading channels, what's more, the lower-bound closed-form expressions of OP for secondary user is obtained. Finally, we perform Monte-Carlo simulations to demonstrate our derivations.

System Model

The cognitive AF relay network with two primary users S and D , and the secondary network consist of $N + 1$ energy harvesting users denoted as C and R_k ($k = 1, 2, \dots, N$) respectively. Primary user S attempts to transmit data to D , however, the distance between S and D beyond the range of effective communication, so, there is not a direct link between primary users. Fortunately, R_k is willing to act as a relay to assist primary transmission so that it can access the licensed band and transmits its own information to secondary user C . We suppose that the primary user S has constant power supply, i.e., P , while there is no energy provided for relay R_k . All nodes are equipped with one single antenna and operate in half-duplex mode.

The whole communication takes place in two phases. In the first phase, primary user S transmits information to secondary network. In the second phase, R_k harvests energy from the part of its received signal from S , and employs the harvested energy to deliver the resulting information with the messages prepared for user C . Due to the wireless broadcast nature, C can also receives the primary signal in phase 1. Thus, secondary user C can also harvest energy from primary signal and use remaining power to cancel interference in phase 2.

Let us denote $h_{1k}, h_{2k}, h_{3k}, h_{4k}$ as the channel coefficients of the links $S \rightarrow R_k, R_k \rightarrow D, R_k \rightarrow C$ and $S \rightarrow C$, respectively. All the channels between two nodes undergo the Rayleigh fading channel. Accordingly, the channel power gains of these channels $|h_{1k}|^2, |h_{2k}|^2, |h_{3k}|^2$ and $|h_{4k}|^2$ follow exponential distribution with mean power $\Omega_1, \Omega_2, \Omega_3, \Omega_4$ respectively.

In phase 1, user S sends information to secondary network, thus, the signal received at user R_k and user C can be expressed as

$$y_{R_k} = \sqrt{P} h_{1k} x_S + n_1 \text{ and } y_C = \sqrt{P} h_{4k} x_S + n_2 \quad (1)$$

respectively. Where x_S is the unit-power signal prepared for node D . $n_j \sim \mathcal{CN}(0, \sigma_0^2)$, ($j = 1, 2$) is the Gaussian noise introduced by the antenna at relay R_k and user C respectively.

In [8], the received signals can be divided into two sections by relay, one for energy harvesting and the other one for information transfer. Similar to [9, Eq. (4)], the energy harvested at node R_k can be calculated as

$$E_{R_k} = \frac{1}{2} \eta \lambda_1 P |h_{1k}|^2 \quad (2)$$

where $\lambda_1 \in (0, 1)$ are the fraction of information split for energy harvesting at node R_k , $\eta \in [0, 1]$ represents the energy conversion efficiently. Coefficient $1/2$ denotes the time duration of each phase.

In order to improve the performance of the cognitive network, we consider a relay selection scheme based on energy harvesting and information transfer protocol at N relays. The relay has highest harvested energy will be selected to forward the information in phase 2. Therefore, the chosen relay can be denoted as R_{k^*} , is selected as

$$k^* = \arg \max_{k \in \mathcal{R}} E_{R_k} \quad (3)$$

where \mathcal{R} denotes the set of relays, $\mathcal{R} = \{R_k | k = 1, 2, \dots, N\}$, equation (3) can be simplified as

$$k^* = \arg \max_{k \in \mathcal{R}} |h_{1k}|^2 \quad (4)$$

Therefore, the transmit power of the selected relay is given as

$$P_{R_{k^*}} = \eta \lambda_1 P |h_{1k^*}|^2 \quad (5)$$

As described in [9], relay R_{k^*} uses a fraction α ($0 < \alpha < 1$) of its received power to forward

the remaining primary information while $1 - \alpha$ of its received power to send secondary signals prepared for user C simultaneously.

According to [9, Eq. (14)], the signal to interference plus noise ratio (SINR) at D is given by

$$\gamma_D = \frac{\eta \lambda_1 \alpha P |h_{1k^*}|^2 |h_{2k^*}|^2}{(1-\alpha) \eta \lambda_1 P |h_{1k^*}|^2 |h_{2k^*}|^2 + \frac{\eta \lambda_1 \alpha}{1-\lambda_1} |h_{2k^*}|^2 \sigma_0^2 + \sigma_0^2} \quad (6)$$

In phase 1, $0 < \lambda_2 < 1$ represents the fraction of information split for energy harvesting at node C , user C will store the energy from the received signal, and the remaining information $\sqrt{1 - \lambda_2} y_C$ will be used to cancel the primary interference in next hop. Likewise, The SNR at user C can be written as [9, Eq. (15)]

$$\gamma_C = \frac{\eta \lambda_1 (1 - \alpha) P |h_{1k^*}|^2 |h_{3k^*}|^2 |h_{4k^*}|^2}{\frac{\alpha \eta \lambda_1 \sigma_0^2}{1-\lambda_2} |h_{1k^*}|^2 |h_{3k^*}|^2 + \frac{\alpha \eta \lambda_1 \sigma_0^2}{1-\lambda_1} |h_{3k^*}|^2 |h_{4k^*}|^2 + \sigma_0^2 |h_{4k^*}|^2} \quad (7)$$

Outage Probability analysis

In this section, we will study the performance of the cognitive AF relay network in terms of OP over Rayleigh fading channels. For user D , we present the exact OP expression. For user C , we give the exact OP expression and the closed-form of lower bound.

The OP is the probability that the instantaneous SNR at user $i, i = D, C$, falls below a predefined threshold, γ_{th} , namely

$$P_{out}^i = \Pr(\gamma_i < \gamma_{th}) = F_{\gamma_i}(\gamma_{th}) \quad (8)$$

where $F_{\gamma_i}(\gamma_{th})$ denotes cumulative distribution function (CDF) of the instantaneous SNR at user i , evaluated at $\gamma_{th} = \gamma$.

For primary user D , if $\gamma \geq a/b$ the CDF of γ_D , $F_{\gamma_D}(\gamma) = 1$, and the OP of primary user D equal to 1.

Otherwise, the CDF can be expressed as

$$\begin{aligned} F_{\gamma_D}(\gamma) &= \int_0^\infty \Pr \left[\frac{a g_1 g_2}{b g_1 g_2 + e g_2 + 1} \leq \gamma | g_1 \right] f_{g_1}(x) dx \\ &= \int_0^{\frac{e\gamma}{a-b\gamma}} \Pr \left[g_2 \geq \frac{\gamma}{(a-b\gamma) g_1 - e\gamma} | g_1 \right] f_{g_1}(x) dx \\ &\quad + \int_{\frac{e\gamma}{a-b\gamma}}^\infty \Pr \left[g_2 \leq \frac{\gamma}{(a-b\gamma) g_1 - e\gamma} | g_1 \right] f_{g_1}(x) dx \\ &= \xi_1 + \xi_2 \end{aligned} \quad (9)$$

where $g_1 = |h_{1k^*}|^2$ and $g_2 = |h_{2k^*}|^2$. $a = \alpha \eta \lambda_1 P / \sigma_0^2$, $b = (1 - \alpha) \eta \lambda_1 P / \sigma_0^2$, $e = \alpha \eta \lambda_1 / (1 - \lambda_1)$, and

$$\xi_1 = \int_0^{\frac{e\gamma}{a-b\gamma}} f_{g_1}(x) dx = F_{g_1} \left(\frac{e\gamma}{a-b\gamma} \right) \quad (10)$$

$$\xi_2 = \int_{\frac{e\gamma}{a-b\gamma}}^\infty F_{g_2} \left(\frac{\gamma}{(a-b\gamma) g_1 - e\gamma} \right) f_{g_1}(x) dx = 1 - F_{g_1} \left(\frac{e\gamma}{a-b\gamma} \right) - \xi_3 \quad (11)$$

$$\xi_3 = \sum_{n=0}^N \binom{N}{n} (-1)^{n-1} \exp \left(-\frac{ne\gamma}{\Omega_1 (a-b\gamma)} \right) \sqrt{\frac{4\gamma n}{\Omega_2 \Omega_1 (a-b\gamma)}} K_1 \left(\sqrt{\frac{4\gamma n}{\Omega_2 \Omega_1 (a-b\gamma)}} \right) \quad (12)$$

With the help of (10), (11), (12), we can obtain (9). According to (8), we can get the OP of user D

$$P_{out}^D = 1 - \sum_{n=1}^N \binom{N}{n} (-1)^{n-1} \exp \left(-\frac{ne\gamma}{\Omega_1 (a-b\gamma)} \right) \sqrt{\frac{4\gamma n}{\Omega_1 \Omega_2 (a-b\gamma)}} K_1 \left(\sqrt{\frac{4\gamma n}{\Omega_2 \Omega_1 (a-b\gamma)}} \right) \quad (13)$$

For secondary user C , the CDF of γ_C can be expressed as

$$\begin{aligned} F_{\gamma_C}(\gamma) &= \Pr \left[\frac{b g_1 g_4 g_3}{g_4 + e g_4 g_3 + d g_1 g_3} < \gamma \right] \\ &= \Pr \left[g_1 \leq \frac{\gamma g_4 (1 + e g_3)}{g_3 (b g_4 - d\gamma)} | g_4 > \frac{d\gamma}{b} \right] \Pr \left[g_4 > \frac{d\gamma}{b} \right] + \Pr \left[g_4 \leq \frac{d\gamma}{b} \right] \end{aligned} \quad (14)$$

where $g_3 = |h_{3k^*}|^2$, $g_4 = |h_{4k^*}|^2$ and $d = \alpha\eta\lambda_1/(1 - \lambda_2)$.

We have

$$\Pr \left[g_4 > \frac{d\gamma}{b} \right] = \exp\left(-\frac{d\gamma}{b\Omega_4}\right) = \Theta_1 \quad (15)$$

$$\Pr \left[g_4 \leq \frac{d\gamma}{b} \right] = 1 - \exp\left(-\frac{d\gamma}{b\Omega_4}\right) = 1 - \Theta_1 \quad (16)$$

and

$$\begin{aligned} \Pr \left[g_1 \leq \frac{\gamma g_4 (1 + e g_3)}{g_3 (b g_4 - d\gamma)} \mid g_4 > \frac{d\gamma}{b} \right] &= \int_0^\infty \int_{\frac{d\gamma}{b}}^\infty F_{g_1} \left(\frac{\gamma y (1 + e z)}{z (b y - d\gamma)} \right) f_{g_3}(y) f_{g_4}(z) dy dz \\ &= \int_0^\infty \int_{\frac{d\gamma}{b}}^\infty f_{g_3}(y) f_{g_4}(z) dy dz - \sum_{n=0}^N \binom{N}{n} (-1)^{n-1} \int_0^\infty \int_{\frac{d\gamma}{b}}^\infty \exp \left(-\frac{\gamma n y (1 + e z)}{\Omega_1 z (b y - d\gamma)} \right) \\ &\quad \times \frac{1}{\Omega_4} \exp \left(-\frac{y}{\Omega_4} \right) \frac{1}{\Omega_3} \exp \left(-\frac{z}{\Omega_3} \right) dy dz \\ &= \Theta_1 - \Theta_2 \end{aligned} \quad (17)$$

and

$$\begin{aligned} \Theta_2 &= \sum_{n=0}^N \binom{N}{n} \frac{(-1)^{n-1}}{\Omega_3} \int_0^\infty \exp \left(-\frac{z}{\Omega_3} - \frac{\gamma n (1 + e z)}{b \Omega_1 z} - \frac{d\gamma}{\Omega_4 b} \right) \\ &\quad \times \sqrt{\frac{4d\gamma^2 (1 + e z) n}{z \Omega_4 \Omega_1 b^2}} K_1 \left(\sqrt{\frac{4d\gamma^2 (1 + e z) n}{z \Omega_4 \Omega_1 b^2}} \right) dz \end{aligned} \quad (18)$$

It is difficult to derive the closed-form of Θ_2 , however, the tight upper bound can be obtained

$$\begin{aligned} \Theta_2 &= \sum_{n=0}^N \binom{N}{n} \frac{(-1)^{n-1}}{\Omega_3} \exp \left(-\frac{\gamma n e}{b \Omega_1} - \frac{d\gamma}{\Omega_4 b} \right) \int_0^\infty z^{-2} \exp \left(-\frac{1}{\Omega_3 z} - \frac{\gamma n z}{b \Omega_1} \right) \\ &\quad \times \sqrt{\frac{4d\gamma^2 (z + e) n}{\Omega_4 \Omega_1 b^2}} K_1 \left(\sqrt{\frac{4d\gamma^2 (z + e) n}{\Omega_4 \Omega_1 b^2}} \right) dz \\ &\leq \sum_{n=0}^N \binom{N}{n} \frac{(-1)^{n-1}}{\Omega_3} \exp \left(-\frac{\gamma n e}{b \Omega_1} - \frac{d\gamma}{\Omega_4 b} \right) \\ &\quad \times \sqrt{\frac{4d\gamma^2 e n}{\Omega_4 \Omega_1 b^2}} K_1 \left(\sqrt{\frac{4d\gamma^2 e n}{\Omega_4 \Omega_1 b^2}} \right) \int_0^\infty z^{-2} \exp \left(-\frac{1}{\Omega_3 z} - \frac{\gamma n z}{b \Omega_1} \right) dz \\ &= \sum_{n=0}^N \binom{N}{n} (-1)^{n-1} \exp \left(-\frac{\gamma n e}{b \Omega_1} - \frac{d\gamma}{\Omega_4 b} \right) \\ &\quad \times \sqrt{\frac{4d\gamma^2 e n}{\Omega_4 \Omega_1 b^2}} K_1 \left(\sqrt{\frac{4d\gamma^2 e n}{\Omega_4 \Omega_1 b^2}} \right) \sqrt{\frac{4\gamma n}{b \Omega_1 \Omega_3}} K_1 \left(\sqrt{\frac{4\gamma n}{b \Omega_1 \Omega_3}} \right) \end{aligned} \quad (19)$$

With the help of (15), (16), (18), (17), we can get the exact CDF of (14). Thus the exact expression of OP for user C can be obtained as

$$\begin{aligned} P_{out}^C &= 1 + \exp\left(-\frac{2d\gamma}{b\Omega_4}\right) - \exp\left(-\frac{d\gamma}{b\Omega_4}\right) - \sum_{n=1}^N \binom{N}{n} (-1)^{n-1} \frac{1}{\Omega_3} \exp\left(-\frac{d\gamma}{b\Omega_4}\right) \\ &\quad \times \int_0^\infty \exp \left(-\frac{z}{\Omega_3} - \frac{\gamma n (1 + e z)}{b \Omega_1 z} - \frac{d\gamma}{b\Omega_4} \right) \sqrt{\frac{4d\gamma^2 n (1 + e z)}{z \Omega_1 \Omega_4 b^2}} K_1 \left(\sqrt{\frac{4d\gamma^2 n (1 + e z)}{z \Omega_1 \Omega_4 b^2}} \right) dz \end{aligned} \quad (20)$$

And the (18) can be replaced by (19), the tight lower bound of OP for secondary user C in closed-form can be deduced as

$$P_{out}^{lower} = 1 + \exp\left(-\frac{2d\gamma}{b\Omega_4}\right) - \exp\left(-\frac{d\gamma}{b\Omega_4}\right) - \sum_{n=1}^N \binom{N}{n} (-1)^{n-1} \times \exp\left(-\frac{\gamma ne}{b\Omega_1} - \frac{2d\gamma}{b\Omega_4}\right) \text{sqr}t \frac{4d\gamma^2 ne}{\Omega_1 \Omega_4 b^2} K_1\left(\sqrt{\frac{4d\gamma^2 ne}{\Omega_1 \Omega_4 b^2}}\right) \sqrt{\frac{4\gamma n}{\Omega_1 \Omega_3 b}} K_1\left(\sqrt{\frac{4\gamma n}{\Omega_1 \Omega_3 b}}\right) \quad (21)$$

Simulation Results

In this section, Monte Carlo simulation results are presented to demonstrate the correctness and effectiveness of our analytical expressions in improved cognitive AF relays model. In particular, we investigate the impact of P/σ_0^2 , power split factor α and the number of AF relays on OP of primary user D and secondary user C . We set the parameters $\Omega_1 = \Omega_2 = 8$, $\Omega_3 = 16$, $\Omega_4 = 64$, $\eta = 1$, $\lambda_1 = 0.25$, $\lambda_2 = 0.15$.

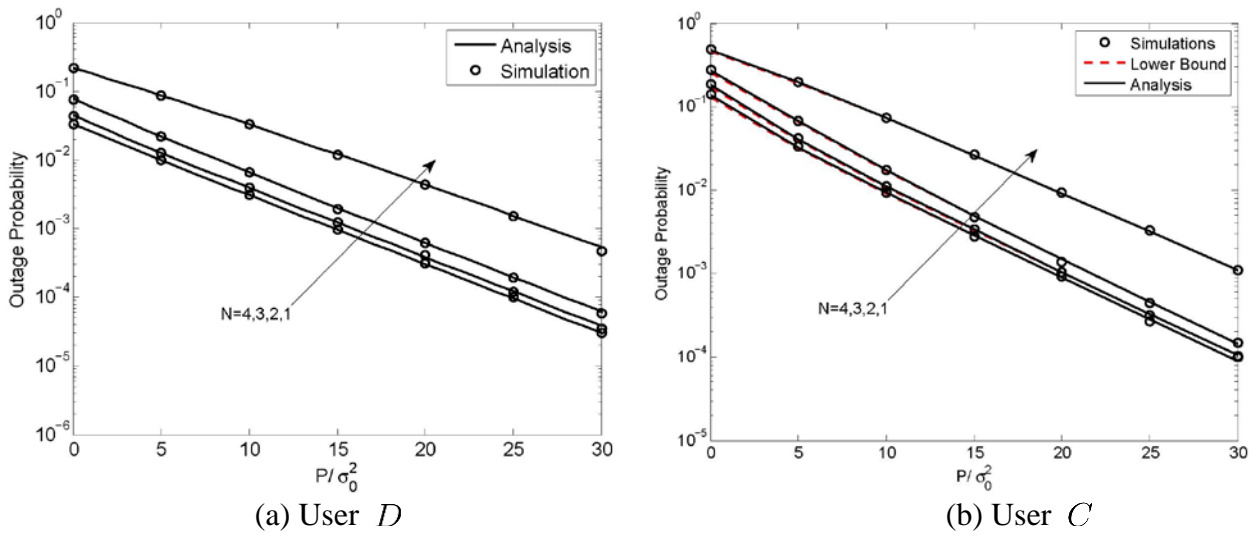


Fig. 1. Outage probability versus the P/σ_0^2 at different values of the number of relays, N

Fig. 1 draw the OP of primary user D and secondary user C versus P/σ_0^2 at different values of the number of relays N respectively, when $\alpha = 0.8$, $\gamma_{th} = 1/2$. As it can be clearly seen from two pictures, the simulated and analytical OP curves match wonderfully. In addition, the OP of primary user D and secondary user C reduce when the value of N increases. This is because that with higher number of R_s , the probability of secondary users can share the spectrum is higher. Finally, the outage performance of primary and secondary network significantly increases at high P/σ_0^2 region. Because with high transmit power, the secondary user can harvest more energy to broadcast primary and secondary data.

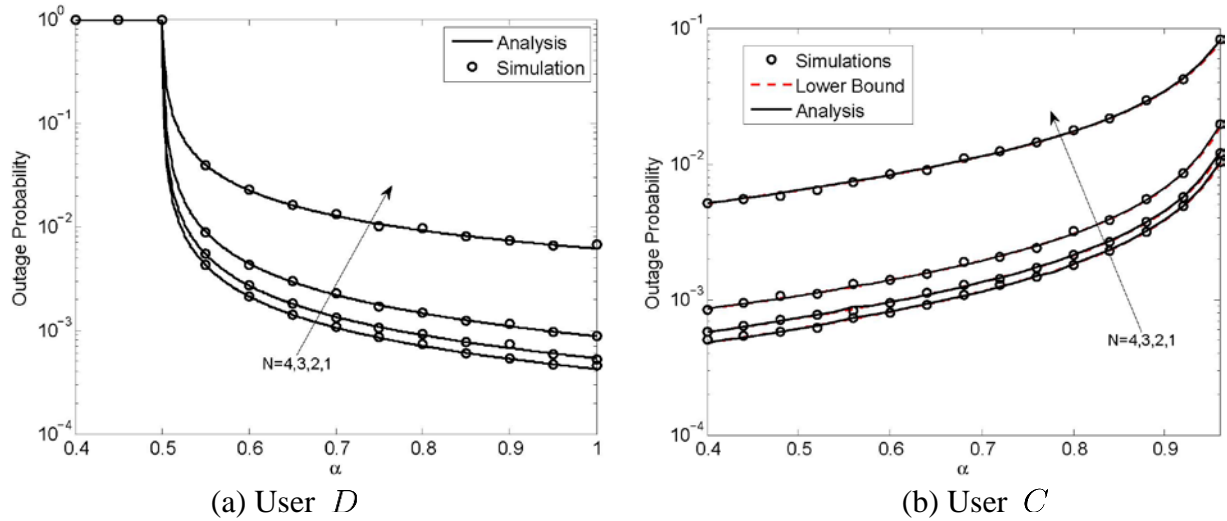


Fig. 2. Outage probability versus the α at different values of the number of relays, N

Fig. 2 show the OP performance of improve cognitive AF relays model versus the power split coefficient α with $P/\sigma_0^2 = 20$ (dB) and $\gamma_{th} = 1$ at primary user D and secondary user C . For Fig. 2 (a), the value of α is varied from 0.4 to 1. It can be seen that the OP equal to 1 when $\alpha \leq 0.5$, this duo to $P/\sigma_0^2 \rightarrow \infty$, $\gamma_D = \alpha/(1-\alpha) \leq \gamma_{th}$. While $\alpha > 0.5$, the OP decreases along with the increase of the α . This is because that more power available to transmit the primary information with the higher value of α . On the contrary to Fig. 2 (a), the OP of secondary user C in Fig. 2 (b) increases along with the increase of power split coefficient α . This can be explained that the more power is split to broadcast primary information, the less power is available to transfer secondary message.

Finally, we can see from Fig. 1 and Fig.2 that the analytical results (Exact) and the simulation results (Simulations) are perfectly matched, which verifies our derivations.

Conclusion

In this paper, we propose the cognitive dual-hop AF relays model with relay selection, and consider the energy harvesting and information transfer protocol. When more relays are available, the outage performance for both primary and secondary networks will be enhanced. We have derived the expression of OP under Rayleigh fading channel, which is also verified by the Monte-Carlo simulation. What's more, the numerical results presented that the proposed system model improves the outage performance when more relays are available.

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