

Performance Enhancement for Harvest-to-Transmit Cognitive Multi-hop Networks with Best Path Selection Method under Presence of Eavesdropper

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Abstract—This paper proposes a path-selection protocol to enhance outage performance for harvest-to-transmit (HT) multi-hop cooperative cognitive radio networks. In the proposed protocol, one of available paths between a secondary source and a secondary destination is chosen to send the source data to the destination. The source and relays on the selected path must harvest energy from the radio frequency (RF) signals of ambient beacons for the data transmission. Under the presence of a primary user (PU) and a secondary eavesdropper (E), these transmitting nodes also have to adjust their transmit power to satisfy an interference constraint given by PU as well as to against eavesdropping attacks from E. For performance evaluation, we derive exact and asymptotic closed-form expressions of end-to-end outage probability (OP) for the proposed scheme over Rayleigh fading channel. Monte Carlo simulations are then performed to validate the theoretical derivations.

Keywords—Physical-layer security, underlay cognitive radio, energy harvesting, multi-hop transmission, path selection, outage probability.

I. INTRODUCTION

Physical-layer security (PLS) [1], [2] has recently emerged as a simple method to obtain secured communication without using upper-layer data encryption. In PLS, secrecy performance is evaluated via secrecy capacity defined as the difference from channel capacity of data links to that of eavesdropping links. To enhance performance for secured communication protocols, diversity protocols [3], [4], [5] can be used to improve data rate for the data links. In [6], [7], security enhancement protocols in underlay cognitive networks were proposed and analyzed. In underlay cognitive radio (UCR), the transmitters must adjust their transmit power to satisfy interference constraints required by primary users (PUs). The authors of [8] studied the security-reliability tradeoff in UCR networks by calculating intercept probability (IP) at an eavesdropper and outage probability (OP) at authorized receivers. In [9], the transmitting nodes including source and relays on the source-destination route can reduce their transmit power to minimize IP at an active eavesdropper.

In non-infrastructure networks such as wireless sensor networks (WSNs) [10], mobile ad-hoc networks (MANETs) [11], cognitive radio ad-hoc networks (CRAHNS) [12], wireless devices that are limited by battery energy have to harvest power from environmental sources to sustain their operation. Recently, radio frequency (RF) energy harvesting (EH) [10],

[13] has been gained much attention as an efficient method for the energy-limited wireless networks. The RF EH techniques allow nodes to collect energy from RF signals of wireless sources. In [14], [15], the authors proposed secured communication protocols with the RF EH techniques. Particularly, published work [14] investigated secrecy outage probability of a simultaneous wireless information and power transfer system consisting of one base station, one desired information receiver, multiple primary users, and multiple EH receivers in UCR systems. By considering the fact that the EH receivers can play as eavesdroppers, the authors in [14] derived expressions of secrecy outage probability for the proposed protocol over Rayleigh fading channel. In [15], a friendly rechargeable cooperative jammer with the presence of a rechargeable source was used to against eavesdropping.

All of the above works have given useful guidance on the performance of EH-based PLS to help system designers to make precise decisions. However, most of them only focus on dual-hop relaying networks, but multi-hop relaying ones. Motivated by the above issues, in this paper, we proposed one innovative protocol in order to enhance outage performance for multi-hop multi-path decode-and-forward (DF) UCR networks. In the proposed protocol, there exist multiple paths between a secondary source and a secondary destination, and one of them is selected to relay the source data to the destination [16]. The source and relays on the selected path must harvest energy from the RF signals of ambient beacons for the data transmission [17]. Under the presence of a primary user (PU) and a secondary eavesdropper (E), these transmitting nodes have to adjust their transmit power to satisfy an interference constraint given by PU as well as to avoid the eavesdropping from E. We propose a best-path selection (BPS) method to maximize the end-to-end instantaneous channel capacity. For performance evaluation, we derive exact and asymptotic closed-form expressions of end-to-end outage probability (OP) for the proposed method over Rayleigh fading channel. Then, simulation results using Monte Carlo method are performed to verify our derivations.

The paper is organized as follows. Section II describes the system model used in this paper. The performance evaluation is shown in section III. The simulation results are shown in section IV. Finally, the paper is concluded in section V.

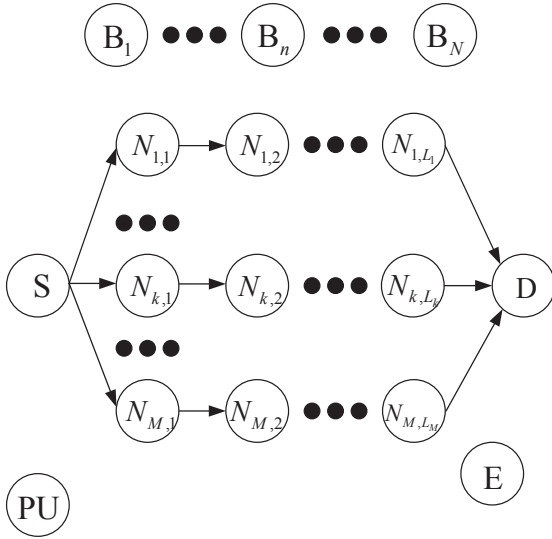


Fig. 1: Secured communication in harvest-to-transmit cognitive multi-hop multi-path networks under presence of secondary eavesdropper.

II. SYSTEM MODEL

In Fig. 1, we present the system model of the proposed protocol, in which a secondary source S communicates with a secondary destination via a multi-hop multi-path scenario. It is assumed that there are M paths between the source and the destination; and one path is selected for the source-destination communication. We also assume that there are L_k relay nodes on the k -th path, which are denoted by $N_{k,1}, N_{k,2}, \dots, N_{k,L_k}$ where $k = 1, 2, \dots, M$.

We assume that all of the secondary transmitters including source and relays are energy-constrained devices which have to harvest the radio frequency (RF) signals from beacons (denoted by $B_1, B_2, \dots, B_N$) for the data transmission. In addition, the secondary transmitters must adjust their transmit power so that the interferences generated their operations are not harmful to the primary users quality of service. In the secondary network, there exists a secondary eavesdropper E , which tries to overhear the data transmitted by the source and the relay nodes. Assume that all of the secondary nodes are equipped with a single antenna; therefore, the data transmission is realized by time division multiple access (TDMA) over orthogonal time slots.

Let us denote $\gamma_{0,P}, \gamma_{0,E}$ and γ_{0,B_n} as the channel gain of the $S \rightarrow PU$, $S \rightarrow E$, and $S \rightarrow B_n$ links, respectively, where $n = 1, 2, \dots, N$. We also denote $\gamma_{0,k}$ as the channel gain of the first hop between the source S and the relay $N_{k,1}$, where $k = 1, 2, \dots, M$. Next, let us denote $\gamma_{j,k}, \gamma_{j,k,P}, \gamma_{j,k,E}$ and γ_{j,k,B_n} as the channel gains of the $N_{k,j} \rightarrow N_{k,j+1}$, $N_{k,j} \rightarrow P$, $N_{k,j} \rightarrow E$ and $N_{k,j} \rightarrow B_n$, respectively, where $j = 1, 2, \dots, L_k$. Assume that all of the channels are Rayleigh fading. Therefore,

channel gains have exponential distributions. Let us denote $\lambda_{0,P}, \lambda_{0,E}, \lambda_{0,B}, \lambda_{0,k}, \lambda_{j,k}, \lambda_{j,k,P}, \lambda_{j,k,E}$, and λ_{j,k,B_n} as parameters of exponential random variables (RVs) and respectively. To take path-loss into account, we can model these parameters as $\lambda = d^\beta$ where β is the path-loss exponent and d is the link distance between two nodes.

Considering the data transmission on the k -th path. Let us denote T as duration of the data transmission from the source to the destination. At the first time slot with time $\tau_k = T/(L_k + 1)$, the source uses duration $\alpha\tau_k$ to harvest the energy from N beacons, where $0 \leq \alpha \leq 1$. The energy harvested by the source is given as

$$EH = \eta\alpha\tau_k P \sum_{n=0}^N \gamma_{0,B_n}, \quad (1)$$

where P is transmit power of the beacons.

Then, the source uses the time $(1 - \alpha)\tau_k$ to transmit its data to the relay $N_{k,1}$. The maximum transmit power of the source from the energy harvesting is given as

$$P_S^{\max} \leq P_S^{EH} = \frac{EH}{(1 - \alpha)\tau_k} = \frac{\eta\alpha\tau_k P \sum_{n=0}^N \gamma_{0,B_n}}{(1 - \alpha)\tau_k} = Z_{0,B}, \quad (2)$$

where $\kappa = \eta\alpha/(1 - \alpha)$ and $Z_{0,B} = \kappa P \sum_{n=0}^N \gamma_{0,B_n}$.

Operating on the underlay mode, the constraint on the transmit power of the source S is formulated by

$$P_S^{\max} \leq \frac{Q}{\gamma_{0,P}}, \quad (3)$$

where Q is interference constraint.

Now, let us consider the channel capacity obtained at the eavesdropper due to the transmission of the source S :

$$C_{S \rightarrow E} = (1 - \alpha)\tau_k \log_2(1 + P_S^{\max} \gamma_{0,E}). \quad (4)$$

In order to avoid the eavesdropper from the eavesdropping, we have the following condition:

$$C_{S \rightarrow E} \leq R \Leftrightarrow P_S^{\max} \leq \frac{\rho_k}{\gamma_{0,E}}, \quad (5)$$

where R is target rate of the secondary network and $\rho_k = 2^{R/(1-\alpha)\tau_k} - 1$.

From (2), (3) and (5), the maximum transmit power of the source can be given as

$$P_S^{\max} = \min\left(Z_{0,B}, \frac{Q}{\gamma_{0,P}}, \frac{\rho_k}{\gamma_{0,E}}\right). \quad (6)$$

Therefore, the channel capacity obtained on the $S \rightarrow N_{k,1}$ link is calculated by

$$\begin{aligned} C_{0,k} &= (1 - \alpha)\tau_k \log_2(1 + P_S^{\max} \gamma_{0,k}) \\ &= (1 - \alpha)\tau_k \log_2\left(1 + \min\left(Z_{0,B}, \frac{Q}{\gamma_{0,P}}, \frac{\rho_k}{\gamma_{0,E}}\right) \gamma_{0,k}\right). \end{aligned} \quad (7)$$

Then, the relay $N_{k,1}$ uses the randomize-and-forward (RF) technique [9] to relay the source data to the destination at the second time slot. Generally, the node $N_{k,j}$ will transmit the

source data to the node $N_{k,j+1}$ using the $(j+1)$ -th time slot. Similarly, the obtained channel capacity on the $N_{k,j} \rightarrow N_{k,j+1}$ link can be given as

$$C_{j,k} = (1 - \alpha) \tau_k \log_2 \left(1 + \min \left(Z_{j,k,B}, \frac{Q}{\gamma_{j,P}}, \frac{\rho_k}{\gamma_{j,E}} \right) \gamma_{j,k} \right), \quad (8)$$

where $Z_{j,k,B} = \kappa P \sum_{n=0}^N \gamma_{j,k,B,n}$.

Next, the end-to-end channel capacity of the k -th path is computed by

$$C_k^{e2e} = \min_{j=1,2,\dots,L_k+1} (C_{j,k}) = (1 - \alpha) \tau_k \log_2 \left(1 + \min_{j=1,2,\dots,L_k+1} \left(\min \left(Z_{j,k,B}, \frac{Q}{\gamma_{j,P}}, \frac{\rho_k}{\gamma_{j,E}} \right) \gamma_{j,k} \right) \right). \quad (9)$$

To optimize the system performance, the best path selection (BPS) protocol is selected as follows:

$$\text{path } a : C_a^{e2e} = \max_{k=1,2,\dots,M} (C_k^{e2e}). \quad (10)$$

Equation (10) implies that the end-to-end instantaneous channel capacity obtained on the path a is highest.

III. PERFORMANCE EVALUATION

In this section, we analyze the end-to-end outage probability (OP) of the proposed method, which is defined by

$$\begin{aligned} \text{OP}_{\text{BPS}} &= \Pr(C_a^{e2e} < R) = \Pr \left(\max_{k=1,2,\dots,M} (C_k^{e2e}) < R \right) \\ &= \prod_{k=1}^M \Pr(C_k^{e2e} < R) \\ &= \prod_{k=1}^M \text{OP}_k, \end{aligned} \quad (11)$$

where OP_k is the outage probability at the k -th path. Using (9), the outage probability (OP_k) can be rewritten by

$$\begin{aligned} \text{OP}_k &= \Pr \left(\min_{j=1,2,\dots,L_k+1} \left(\min \left(Z_{j,k,B}, \frac{Q}{\gamma_{j,P}}, \frac{\rho_k}{\gamma_{j,E}} \right) \gamma_{j,k} \right) < \rho_k \right) \\ &= 1 - \prod_{j=1}^{L_k+1} (1 - \text{OP}_{j,k}), \end{aligned} \quad (12)$$

where $\text{OP}_{j,k}$ is the outage probability at the j -th hop, $j = 1, 2, \dots, L_k + 1$. Firstly, we can rewrite $\text{OP}_{j,k}$ by

$$\begin{aligned} \text{OP}_{j,k} &= \Pr \left(\min \left(Z_{j,k,B}, \frac{Q}{\gamma_{j,P}}, \frac{\rho_k}{\gamma_{j,E}} \right) \gamma_{j,k} < \rho_k \right) \\ &= \int_0^{+\infty} F_X \left(\frac{\rho_k}{y} \right) f_{\gamma_{j,k}}(y) dy, \end{aligned} \quad (13)$$

where $X = \min \left(Z_{j,k,B}, \frac{Q}{\gamma_{j,P}}, \frac{\rho_k}{\gamma_{j,E}} \right)$, $F_X(\cdot)$ is the cumulative distribution function (CDF) of X , and $f_{\gamma_{j,k}}(\cdot)$ is the probability density function (PDF) of $\gamma_{j,k}$.

Now, our objective is find the CDF of X , we have

$$\begin{aligned} F_X(x) &= \Pr(X \leq x) \\ &= \Pr \left(\min \left(Z_{j,k,B}, \frac{Q}{\gamma_{j,P}}, \frac{\rho_k}{\gamma_{j,E}} \right) < x \right) \\ &= 1 - \Pr \left(Z_{j,k,B} \geq x \right) \Pr \left(\gamma_{j,P} < \frac{1}{x} \right) \Pr \left(\gamma_{j,E} < \frac{1}{x} \right) \\ &= 1 - (1 - F_{Z_{j,k,B}}(x)) F_{\gamma_{j,P}} \left(\frac{1}{x} \right) F_{\gamma_{j,E}} \left(\frac{1}{x} \right). \end{aligned} \quad (14)$$

Using the CDF of the summation of exponential RVs, and the CDF of exponential RVs, we obtain

$$\begin{aligned} F_X(x) &= 1 - \sum_{n=0}^{N-1} \frac{\Omega_{j,k,B}^n}{n!} x^n \exp(-\Omega_{j,k,B}) (1 - \exp(-\Omega_{j,P}x)) \\ &\quad \times (1 - \exp(-\Omega_{j,E}x)), \end{aligned} \quad (15)$$

where $\Omega_{j,k,B} = \lambda_{j,k,B} / (\kappa P)$, $\Omega_{j,P} = \lambda_{j,P} Q$, and $\Omega_{j,E} = \lambda_{j,E} \rho_k$.

Substituting (15) and $f_{\gamma_{j,k}}(y) = \lambda_{j,k} \exp(-\lambda_{j,k}y)$ into (13), we obtain

$$\text{OP}_{j,k} = 1 - \sum_{n=0}^{N-1} (I_1 - I_2 - I_3 + I_4), \quad (16)$$

where

$$\begin{aligned} I_1 &= \frac{\rho_k^n \Omega_{j,k,B}^n}{n!} \lambda_{j,k} \int_0^{+\infty} \frac{1}{y^n} \exp \left(-\frac{\Omega_{j,k,B} \rho_k}{y} \right) \exp(-\lambda_{j,k}y) dy, \\ I_2 &= \frac{\rho_k^n \Omega_{j,k,B}^n}{n!} \lambda_{j,k} \int_0^{+\infty} \frac{1}{y^n} \exp \left(-\frac{\Omega_{j,k,B} \rho_k}{y} \right) \\ &\quad \times \exp \left(-(\Omega_{j,k,P} \rho_k + \lambda_{j,k})y \right) dy, \\ I_3 &= \frac{\rho_k^n \Omega_{j,k,B}^n}{n!} \lambda_{j,k} \int_0^{+\infty} \frac{1}{y^n} \exp \left(-\frac{\Omega_{j,k,B} \rho_k}{y} \right) \\ &\quad \times \exp \left(-(\Omega_{j,k,E} \rho_k + \lambda_{j,k})y \right) dy, \\ I_4 &= \frac{\rho_k^n \Omega_{j,k,B}^n}{n!} \lambda_{j,k} \int_0^{+\infty} \frac{1}{y^n} \exp \left(-\frac{\Omega_{j,k,B} \rho_k}{y} \right) \\ &\quad \times \exp \left(-(\Omega_{j,k,P} \rho_k + \Omega_{j,k,E} \rho_k + \lambda_{j,k})y \right) dy. \end{aligned} \quad (17)$$

After some algebraic manipulations, we obtain

$$\begin{aligned} I_1 &= \frac{2}{n!} (\rho_k \Omega_{j,k,B} \lambda_{j,k})^{\frac{n+1}{2}} K_{n-1} \left(2 \sqrt{\rho_k \Omega_{j,k,B} \lambda_{j,k}} \right), \\ I_2 &= \frac{2}{n!} \lambda_{j,k} \rho_k (\Omega_{j,k,B})^{\frac{n+1}{2}} (\lambda_{j,k} \rho_k + \Omega_{j,k,P})^{\frac{n-1}{2}} \\ &\quad \times K_{n-1} \left(2 \sqrt{\Omega_{j,k,B} (\lambda_{j,k} \rho_k + \Omega_{j,k,P})} \right), \\ I_3 &= \frac{2}{n!} \lambda_{j,k} \rho_k (\Omega_{j,k,B})^{\frac{n+1}{2}} (\lambda_{j,k} \rho_k + \Omega_{j,k,E})^{\frac{n-1}{2}} \\ &\quad \times K_{n-1} \left(2 \sqrt{\Omega_{j,k,B} (\lambda_{j,k} \rho_k + \Omega_{j,k,E})} \right), \\ I_4 &= \frac{2}{n!} \lambda_{j,k} \rho_k (\Omega_{j,k,B})^{\frac{n+1}{2}} (\lambda_{j,k} \rho_k + \Omega_{j,k,P} + \Omega_{j,k,E})^{\frac{n-1}{2}} \\ &\quad \times K_{n-1} \left(2 \sqrt{\Omega_{j,k,B} (\lambda_{j,k} \rho_k + \Omega_{j,k,P} + \Omega_{j,k,E})} \right), \end{aligned} \quad (18)$$

where $K_{n-1}(\cdot)$ is modified Bessel function of the second kind [18, eq. (8.407.1)].

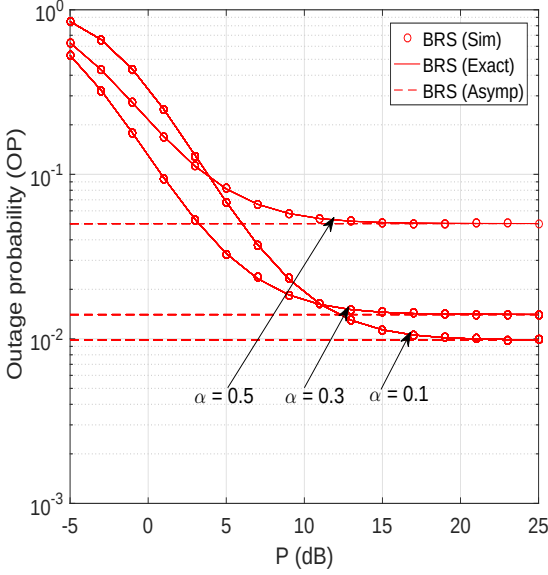


Fig. 2: OP as a function of the transmit power P in dB when $Q = 5$ dB, $L = [3, 4, 5]$, $R = 0.5$, $N = 2$, $(x_B, y_B) = (0.5, 0.25)$, $(x_P, y_P) = (0.5, -1)$, $(x_E, y_E) = (0.5, 0.5)$, $\eta = 0.1$ and $\alpha = 0.1$.

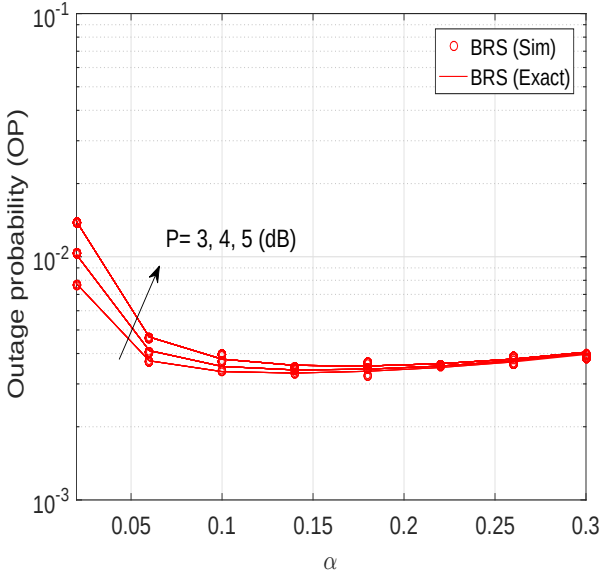


Fig. 3: OP as a function of the fraction α when $Q = 7.5$ dB, $M = 3$, $L = [5, 6, 7]$, $R = 0.5$, $N = 4$, $(x_B, y_B) = (0.5, 0.2)$, $(x_P, y_P) = (0.5, -1)$, $(x_E, y_E) = (0.5, 0.7)$ and $\eta = 0.5$.

Combining (11), (12), (16) and (18), we obtain an exact closed-form expression of OP_{BPS} .

Next, we consider the outage performance of the proposed method at high transmit power, i.e., $P \rightarrow +\infty$. Indeed, at high

P region, we can obtain (19) from (6) as

$$P_S^{\max} \xrightarrow{P \rightarrow +\infty} \min\left(\frac{Q}{\gamma_{0,P}}, \frac{\rho_k}{\gamma_{0,E}}\right). \quad (19)$$

Then, using (19) (instead of (6)) to calculate $OP_{j,k}$, we obtain the approximate expression of $OP_{j,k}$ as follows:

$$\begin{aligned} OP_{j,k} &\xrightarrow{P \rightarrow +\infty} \Pr\left(\min\left(\frac{Q}{\gamma_{j,P}}, \frac{\rho_k}{\gamma_{j,E}}\right) \gamma_{j,k} < \rho_k\right) \\ &\approx \frac{\lambda_{j,k} \rho_k}{\lambda_{j,k} \rho_k + \Omega_{j,k,P}} + \frac{\lambda_{j,k} \rho_k}{\lambda_{j,k} \rho_k + \Omega_{j,k,E}} \\ &\quad - \frac{\lambda_{j,k} \rho_k}{\lambda_{j,k} \rho_k + \Omega_{j,k,P} + \Omega_{j,k,E}}. \end{aligned} \quad (20)$$

Hence, the end-to-end outage probability of the BPS protocol can be approximated as in (21) at the top of next page.

IV. SIMULATION RESULTS

In this section, we provide Monte-Carlo simulations to verify the theoretical derivations. In the simulation environment, we consider a two-dimensional plane in which the coordinates of the source, the relays, the destination, the beacons, the primary user and the eavesdropper are $(0, 0)$, $(j/(L_k + 1), 0)$, $(1, 0)$, (x_B, y_B) , (x_P, y_P) and (x_E, y_E) , respectively. The path-loss exponential η , the duration T , and the variance of noise equal 3, 1 and 1, respectively, in each simulation.

In Fig. 2, we investigate the impact of the transmit power P in dB on the end-to-end outage probability (OP) with various values of the time fraction α , i.e., $\alpha = 0.1, 0.3, 0.5$, when $Q = 5$ dB, $L = [3, 4, 5]$, $R = 0.5$, $N = 2$, $(x_B, y_B) = (0.5, 0.25)$, $(x_P, y_P) = (0.5, -1)$, $(x_E, y_E) = (0.5, 0.5)$, $\eta = 0.1$ and $\alpha = 0.1$. As shown, there is a good agreement between the theoretical and the simulation results. It is observed that, when P is small, OP is high, and when P increases, OP decreases monotonically. This means that increasing the transmit power of can enhance outage performance of the proposed method. Furthermore, comparing the different value of α , Figure 2 illustrates that OP is non-monotonically changing. This point motivates us to investigate the influence of the time fraction α on the OP in Fig. 3.

Figure 3 shows OP versus the time fraction α at three different transmit power, i.e., $P = 3$ dB, $P = 4$ dB, and $P = 5$ dB; when $Q = 7.5$ dB, $M = 3$, $L = [2, 3, 4]$, $R = 0.5$, $N = 4$, $(x_B, y_B) = (0.5, 0.2)$, $(x_P, y_P) = (0.5, -1)$, $(x_E, y_E) = (0.5, 0.7)$, and $\eta = 0.5$. Figure 3 clearly shows that, OP first decreases to a minimum when α attains the optimum value at 0.14, and then increases along with α . This indicates that OP is not monotony of α . Therefore, we can use this optimal value of α to design the practical system. Again, we can see from Fig. 3 that the simulation results are very well matched with the theoretical ones, thereby verifying the derivations of this study.

Figure 4 plots OP as a function of eavesdroppers position at three different transmit power, i.e., $P = 1$ dB, $P = 3$ dB, and $P = 5$ dB. In particular, we change the value of x_E from 0 to 1, while fixing the remain parameters as follows: $Q = 5$ dB, $M = 3$, $L = [3, 4, 5]$, $R = 0.5$, $N = 1$, $(x_B, y_B) = (0.5, 0.1)$, $(x_P, y_P) = (0.5, -1)$, $y_E = 0.4$, $\eta = 1$, and $\alpha = 0.1$. We

$$\text{OP}_{\text{BPS}} \stackrel{P \rightarrow +\infty}{\approx} \prod_{k=1}^M \left[1 - \prod_{j=1}^{L_k+1} \left(1 - \frac{\lambda_{j,k}\rho_k}{\lambda_{j,k}\rho_k + \Omega_{j,k,P}} - \frac{\lambda_{j,k}\rho_k}{\lambda_{j,k}\rho_k + \Omega_{j,k,E}} + \frac{\lambda_{j,k}\rho_k}{\lambda_{j,k}\rho_k + \Omega_{j,k,P} + \Omega_{j,k,B}} \right) \right]. \quad (21)$$

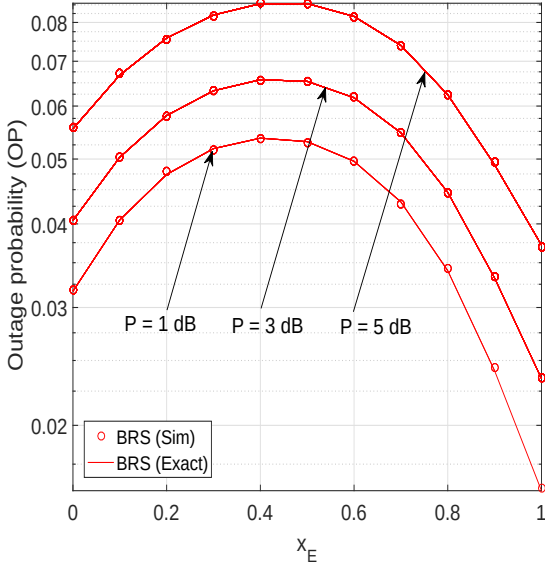


Fig. 4: OP as a function of x_E , when $Q = 7.5$ dB, $M = 3$, $L = [3, 4, 5]$, $R = 0.5$, $N = 1$, $(x_B, y_B) = (0.5, 0.1)$, $(x_P, y_P) = (0.5, -1)$, $y_E = 0.4$, $\eta = 1$ and $\alpha = 0.1$.

can observe that OP of the considered protocol varies with different eavesdroppers position, and it becomes better if the eavesdropper is far away from the source S and the relaying nodes. Moreover, the increasing of transmit power of beacons (P) also has positive effect on the outage performance.

V. CONCLUSION

In this paper, we proposed a novel path selection method to enhance the outage performance for harvest-to-transmit cognitive multi-hop multi-path networks in presence of the eavesdropper. We derived exact and asymptotic closed-form expressions of the end-to-end outage probability for the proposed method over Rayleigh fading channel. Simulation results were performed to verify the theoretical ones. The results presented that outage performance depends on the transmit power of the beacons, the time fraction allocated for the energy harvesting process, and the position of the eavesdropper. Moreover, the optimal value of the time fraction can be efficiently used in designing the considered networks.

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