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Outage Performance of Cooperative Cognitive Radio Networks under Joint Constraints of Co-Channel Interference, Intercept Probability and Hardware Imperfection

Pham Thi Dan Ngoc[1,2], Tran Trung Duy[2,*], Ho Van Khuong[1]

[1]Ho Chi Minh City University of Technology, VNU-HCM, Ho Chi Minh City, Vietnam
[2]Posts and Telecommunications Institute of Technology, Ho Chi Minh City, Vietnam

Abstract

This paper evaluates outage probability (OP) of a cooperative underlay cognitive radio network in the presence of a passive secondary eavesdropper under joint impacts of limited interference from a primary network and hardware impairments. With intercept probability constraint required for the eavesdropper and interference constraint given by a primary receiver, we derive closed-form expressions of transmit power for the secondary transmitters, including source and relays, only relying on the knowledge of statistical channel state information (CSI). Then, a relay selection method is used in the cooperative phase to enhance the OP performance of the considered protocol. For performance evaluation, we derive an exact closed-form expression of OP over Rayleigh fading channel. Finally, we perform Monte Carlo simulations to verify the derived formulas.

Keywords: Physical-layer security, outage probability, intercept probability, underlay cognitive radio.

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1. Introduction

Recently, physical-layer security (PLS) [1]-[3] has gained much attention of researchers as a potential solution to protect the legitimate users without using complex cryptographic methods. In principle, PLS exploits physical-layer characteristics such as channel state information (CSI), link distances to obtain security for wireless communication systems. In [4]-[6], cooperative relay selection methods were proposed to improve secrecy performances in terms of average secrecy capacity, secrecy outage probability, probability of non-zero secrecy capacity. In [4]-[5], the relays are selected in the cooperative phase to protect the destination against the eavesdropper. In [6], the authors proposed a joint beam-forming and relay selection method to obtain PLS for dual-hop relaying networks. To further enhance secrecy performance, cooperative jamming (CJ) techniques [7]-[9] can be used, where jammers are employed to transmit artificial noises on the eavesdropper. In [7], the authors proposed joint relay and jammer selection methods, where the selected relay is used to forward the source data to the destination, while the chosen jammer generates interference on the eavesdropper. The published work [8] evaluated secrecy performance of cooperative cognitive networks with various relay and jammer selection schemes in underlay spectrum sharing approach. In [9], the authors proposed a harvest-to-jam method, where the jammer harvests energy from radio frequency signals for generating noises. However, the implementation of the CJ methods is very complex due to high synchronization between the nodes [10]. Different with [4]-[9], the authors of [10]-[13] evaluated performance of secure communication protocols via intercept probability (IP) of the eavesdropping links and outage probability (OP) of the data links. As showed in [10]-[13], there exists a trade-off

*Corresponding author. Email: Trantrungduy@ptithcm.edu.vn

between security and reliability which can be improved by using relay selection methods.

To obtain high secrecy performance, CSI estimation of the eavesdropping channels has an important role. Indeed, references [14]-[17] assumed that the eavesdroppers are active nodes and hence, the legitimate transmitters/receivers can perfectly obtain the eavesdropping CSIs to optimize the secrecy capacity. However, when the eavesdroppers are passive, the protocols proposed in [14]-[17] cannot be completely applied. In [10], [18]-[19], the authors considered passive eavesdropper schemes, in which the secure transmission is enhanced by knowledge of statistical CSIs of the eavesdropping links. Particularly, the reference [10] proposed two power allocation strategies to reduce the IP value below a desired threshold, while the best relay selection using max-min strategy is used to enhance the end-to-end OP. In [18], the authors proposed a joint relay selection and power allocation method to enhance secrecy performance of a cooperative relaying network in the presence of untrusted relays and passive eavesdroppers. The authors of [19] designed a CJ method for secrecy enhancement in MIMO systems with multiple passive eavesdroppers.

In this paper, we evaluate outage performance of a secure cooperative cognitive radio protocol operating on the underlay approach [8], [13], in terms of OP. In the considered scheme, a secondary source communicates with a secondary destination via the assistance of secondary decode-and-forward (DF) relays, in presence of a passive secondary eavesdropper. Assume that only statistical CSIs of the interference and eavesdropping links are available, we propose a simple power allocation strategy for the secondary source and relays to satisfy both the interference constraint and the IP constraint. Then, we propose a relay selection method to enhance the OP performance for the secondary networks under impact of the co-channel interference from the primary network and the hardware impairments [20]-[22]. For performance evaluation, we derive exact closed-form expression of OP over Rayleigh fading channel. Finally, we perform Monte Carlo simulations to verify the theoretical results. The results presented that the transmit power of the primary transmitter, the number of relays and the position of the relays significantly impact the outage probability.

The rest of this paper is organized as follows. The system model of the proposed protocol is described in Section 2. In Section 3, the exact closed-form expression of OP is derived. The simulation results are shown in Section 4. Finally, this paper is concluded in Section 5.

2. System Model

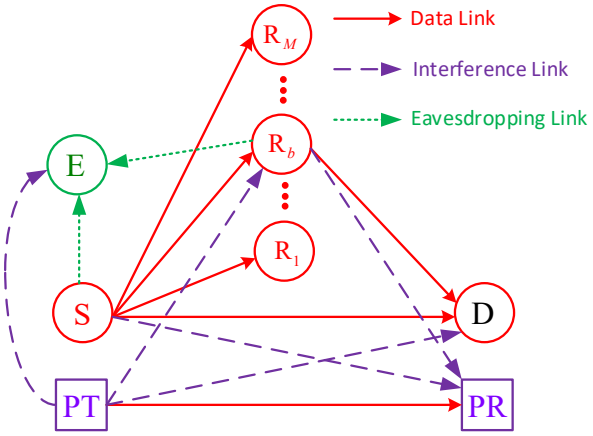

Figure 1. System model of the proposed protocol.

In Fig. 1, the system model of the proposed protocol is shown. In the primary network, a primary transmitter (PT) transmits its data to a primary receiver (PR). In the secondary network, a secondary source (S) attempts to transmit the data to a secondary destination (D) with help from M secondary relays denoted by R_m, where $m = 1, 2, ..., M$. Also in the secondary network, an eavesdropper (E) tries to overhear the source data transmitted by the source and the relays. Assume that all the terminals are equipped with a single antenna and operate in half-duplex mode.

Let $d_{\mathrm{X,Y}}$ and $\gamma_{\mathrm{X,Y}}$ as the distance and channel gain of the $\mathrm{X} \to \mathrm{Y}$ link, respectively, where $\mathrm{X,Y} \in \{\mathrm{PT,PR,S,R}_m, \mathrm{D,E}\}$. Assume that all of the channels follow a block Rayleigh fading distribution which remains coherently constant over the length of a data cycle, hence the channel gain $\gamma_{\mathrm{X,Y}}$ follows an exponential distribution whose cumulative distribution function (CDF) and probability density function (PDFs) are given, respectively as

$$\begin{aligned} F_{\gamma_{\mathrm{X,Y}}}(x) &= 1 - \exp\left(-\lambda_{\mathrm{X,Y}} x\right), \\ f_{\gamma_{\mathrm{X,Y}}}(x) &= \lambda_{\mathrm{X,Y}} \exp\left(-\lambda_{\mathrm{X,Y}} x\right), \end{aligned} \tag{1}$$

where $\lambda_{\mathrm{X,Y}} = d_{\mathrm{X,Y}}^{\beta}$, and β is path-loss exponent [23]-[24]. Assume that the secondary relays are close together, which form a cluster, and hence $d_{\mathrm{X,R}_m} = d_{\mathrm{X,R}}$, $d_{\mathrm{R}_m,\mathrm{Y}} = d_{\mathrm{R,Y}}$ or $\lambda_{\mathrm{X,R}_m} = \lambda_{\mathrm{X,R}}$, $\lambda_{\mathrm{R}_m,\mathrm{Y}} = \lambda_{\mathrm{R,Y}}$ for all m.

2.1. Operation of the proposed protocol

At the first time slot, the source (S) broadcasts its data to the destination and all of the relays. Next, the relays attempt to decode the source data from the received signal. Let us denote Z_1 and Z_2 as the set of the relays that decode the data correctly and incorrectly, respectively. Without loss of generality, we can assume that $Z_1 = \{\mathrm{R}_1, \mathrm{R}_2, ..., \mathrm{R}_K\}$ and $Z_2 = \{\mathrm{R}_{K+1}, \mathrm{R}_{K+2}, ..., \mathrm{R}_M\}$,

where K is the number of the successful relays, $0 \le K \le M$. For example, if $K = 0$, there is no relay which can retransmit the source data to the destination. If $K \ge 1$, one of the successful relays is selected by the following method:

$$\mathrm{R}_b : \gamma_{\mathrm{R}_b,\mathrm{D}} = \max_{k=1,2,\ldots,K} \left(\gamma_{\mathrm{R}_k,\mathrm{D}}\right). \tag{2}$$

Equation (2) implies that the relay providing the highest channel gain to the destination is chosen for the cooperation. Indeed, the R_b relay will re-encode, and transmit the encoded data to the destination at the second time slot. Finally, the destination attempts to decode the source data from the signals received from the source and the selected relay. It is also noted that if $K = 0$, the destination only uses the signal from the source for the decoding process.

Furthermore, S and R_b can employ the randomize-and-forward (RF) technique [25]-[26] to confuse the eavesdropper. Particularly, random code-books are generated by S and R_b to avoid E to combine the received signals with maximal ratio combining (MRC).

2.2. Interference Constraint

The instantaneous signal-to-interference-plus-noise ratios (SINRs) obtained at PR at the first and second time slot of the secondary data transmission can be expressed, respectively as

$$\begin{aligned} \psi_{\mathrm{PT,PR}}^{(1)} &= \frac{P_{\mathrm{PT}}\gamma_{\mathrm{PT,PR}}}{\kappa_{\mathrm{P}}^2 P_{\mathrm{PT}}\gamma_{\mathrm{PT,PR}} + P_{\mathrm{S}}\gamma_{\mathrm{S,PR}} + \sigma^2}, \\ \psi_{\mathrm{PT,PR}}^{(2)} &= \frac{P_{\mathrm{PT}}\gamma_{\mathrm{PT,PR}}}{\kappa_{\mathrm{P}}^2 P_{\mathrm{PT}}\gamma_{\mathrm{PT,PR}} + P_{\mathrm{R}_b}\gamma_{\mathrm{R}_b,\mathrm{PR}} + \sigma^2}, \end{aligned} \tag{3}$$

where κ_{P}^2 is the total level of hardware impairments of the $\mathrm{PT} \to \mathrm{PR}$ link [20]-[22], P_{PT}, P_{S}, P_{R_b} are transmit powers of PT, S and R_b, respectively, and σ^2 is variance of additive white Gaussian noise (AWGN).

Then, the channel capacities between PT and PR in the first and the second time slot can be given, respectively as

$$\begin{aligned} C_{\mathrm{PT,PR}}^{(1)} &= \frac{1}{2}\log_2\left(1+\psi_{\mathrm{PT,PR}}^{(1)}\right), \\ C_{\mathrm{PT,PR}}^{(2)} &= \frac{1}{2}\log_2\left(1+\psi_{\mathrm{PT,PR}}^{(2)}\right), \end{aligned} \tag{4}$$

where the factor ½ indicates that the data transmission of the secondary network is split into two orthogonal time slots.

To protect quality of service (QoS) of the primary network at any time slots, we have to focus on the minimum value of $C_{\mathrm{PT,PR}}^{(1)}$ and $C_{\mathrm{PT,PR}}^{(2)}$, i.e.,

$$\begin{aligned} C_{\mathrm{PT,PR}}^{\min} &= \min\left(C_{\mathrm{PT,PR}}^{(1)}, C_{\mathrm{PT,PR}}^{(2)}\right) \\ &= \frac{1}{2}\log_2\left[1+\min\left(\psi_{\mathrm{PT,PR}}^{(1)}, \psi_{\mathrm{PT,PR}}^{(2)}\right)\right]. \end{aligned} \tag{5}$$

Then, the outage probability of the primary network can be formulated as

$$\begin{aligned} \mathrm{OP}_{\mathrm{P}} &= \Pr\left(C_{\mathrm{PT,PR}}^{\min} < \mathrm{C}_{\mathrm{P}}\right) \\ &= \Pr\left[\min\left(\psi_{\mathrm{PT,PR}}^{(1)}, \psi_{\mathrm{PT,PR}}^{(2)}\right) < \rho_{\mathrm{P}}\right] \\ &= 1 - \Pr\left(\psi_{\mathrm{PT,PR}}^{(1)} \ge \rho_{\mathrm{P}}, \psi_{\mathrm{PT,PR}}^{(2)} \ge \rho_{\mathrm{P}}\right), \end{aligned} \tag{6}$$

where C_{P} is target rate of the primary network, and

$$\rho_{\mathrm{P}} = 2\,\hat{}\,\left(2\mathrm{C}_{\mathrm{P}}\right) - 1. \tag{7}$$

Combining (3)-(6), we can rewrite OP_{P} under the following form:

$$\begin{aligned} \mathrm{OP}_{\mathrm{P}} &= 1 - \Pr\left(\gamma_{\mathrm{PT,PR}} \ge \frac{\theta_{\mathrm{P}} P_{\mathrm{S}}}{P_{\mathrm{PT}}}\gamma_{\mathrm{S,PR}} + \frac{\theta_{\mathrm{P}}\sigma^2}{P_{\mathrm{PT}}}, \right. \\ &\qquad \left. \gamma_{\mathrm{PT,PR}} \ge \frac{\theta_{\mathrm{P}} P_{\mathrm{R}_b}}{P_{\mathrm{PT}}}\gamma_{\mathrm{R}_b,\mathrm{PR}} + \frac{\theta_{\mathrm{P}}\sigma^2}{P_{\mathrm{PT}}}\right) \\ &= 1 - \Pr\left[\gamma_{\mathrm{PT,PR}} \ge \max\left(Z_1, Z_2\right)\right]. \end{aligned} \tag{8}$$

where

$$\begin{aligned} \theta_{\mathrm{P}} &= \frac{\rho_{\mathrm{P}}}{1-\kappa_{\mathrm{P}}^2\rho_{\mathrm{P}}}, Z_1 = \frac{\theta_{\mathrm{P}} P_{\mathrm{S}}}{P_{\mathrm{PT}}}\gamma_{\mathrm{S,PR}} + \frac{\theta_{\mathrm{P}}\sigma^2}{P_{\mathrm{PT}}}, \\ Z_2 &= \frac{\theta_{\mathrm{P}} P_{\mathrm{R}_b}}{P_{\mathrm{PT}}}\gamma_{\mathrm{R}_b,\mathrm{PR}} + \frac{\theta_{\mathrm{P}}\sigma^2}{P_{\mathrm{PT}}}. \end{aligned} \tag{9}$$

Denoting $Z_{\max} = \max\left(Z_1, Z_2\right)$, its CDF can be formulated as

$$\begin{aligned} F_{Z_{\max}}(z) &= \Pr\left(Z_1 < z\right)\Pr\left(Z_2 < z\right) \\ &= \Pr\left(\gamma_{\mathrm{S,PR}} < \frac{P_{\mathrm{PT}}}{\theta_{\mathrm{P}} P_{\mathrm{S}}} z - \frac{\sigma^2}{P_{\mathrm{S}}}\right) \\ &\quad \times \Pr\left(\gamma_{\mathrm{R}_b,\mathrm{PR}} < \frac{P_{\mathrm{PT}}}{\theta_{\mathrm{P}} P_{\mathrm{R}_b}} z - \frac{\sigma^2}{P_{\mathrm{R}_b}}\right). \end{aligned} \tag{10}$$

We can observe from (10) that if $z \le \sigma^2\theta_{\mathrm{P}} / P_{\mathrm{PT}}$, then $F_{Z_{\max}}(z) = 0$, and if $z > \sigma^2\theta_{\mathrm{P}} / P_{\mathrm{PT}}$, we have

$$\begin{aligned} F_{Z_{\max}}(z) &= \left[1 - \exp\left(\frac{\lambda_{\mathrm{S,PR}}\sigma^2}{P_{\mathrm{S}}}\right)\exp\left(-\frac{\lambda_{\mathrm{S,PR}} P_{\mathrm{PT}}}{\theta_{\mathrm{P}} P_{\mathrm{S}}} z\right)\right] \\ &\quad \times \left[1 - \exp\left(\frac{\lambda_{\mathrm{R,PR}}\sigma^2}{P_{\mathrm{R}_b}}\right)\exp\left(-\frac{\lambda_{\mathrm{R,PR}} P_{\mathrm{PT}}}{\theta_{\mathrm{P}} P_{\mathrm{R}_b}} z\right)\right]. \end{aligned} \tag{11}$$

Therefore, if $z \le \sigma^2\theta_{\mathrm{P}} / P_{\mathrm{PT}}$, then $f_{Z_{\max}}(z) = 0$, and if $z > \sigma^2\theta_{\mathrm{P}} / P_{\mathrm{PT}}$, we can obtain PDF of $Z_{\max}$ as

$$f_{Z_{\max}}(z)=\frac{\lambda_{\mathrm{S,PR}}P_{\mathrm{PT}}}{\theta_{\mathrm{P}}P_{\mathrm{S}}}\exp\left(\frac{\lambda_{\mathrm{S,PR}}\sigma^2}{P_{\mathrm{S}}}\right)\exp\left(-\frac{\lambda_{\mathrm{S,PR}}P_{\mathrm{PT}}}{\theta_{\mathrm{P}}P_{\mathrm{S}}}z\right)+\frac{\lambda_{\mathrm{R,PR}}P_{\mathrm{PT}}}{\theta_{\mathrm{P}}P_{\mathrm{R}_b}}\exp\left(\frac{\lambda_{\mathrm{R,PR}}\sigma^2}{P_{\mathrm{R}_b}}\right)\exp\left(-\frac{\lambda_{\mathrm{R,PR}}P_{\mathrm{PT}}}{\theta_{\mathrm{P}}P_{\mathrm{R}_b}}z\right)-\left(\frac{\lambda_{\mathrm{S,PR}}}{P_{\mathrm{S}}}+\frac{\lambda_{\mathrm{R,PR}}}{P_{\mathrm{R}_b}}\right)\frac{P_{\mathrm{PT}}}{\theta_{\mathrm{P}}}\exp\left(\frac{\lambda_{\mathrm{S,PR}}\sigma^2}{P_{\mathrm{S}}}+\frac{\lambda_{\mathrm{R,PR}}\sigma^2}{P_{\mathrm{R}_b}}\right)\times\exp\left[-\left(\frac{\lambda_{\mathrm{S,PR}}}{P_{\mathrm{S}}}+\frac{\lambda_{\mathrm{R,PR}}}{P_{\mathrm{R}_b}}\right)\frac{P_{\mathrm{PT}}}{\theta_{\mathrm{P}}}z\right]. \tag{12}$$

Then, we can rewrite (8) as follows:

$$\mathrm{OP}_{\mathrm{P}}=1-\int_{\frac{\sigma^2\theta_{\mathrm{P}}}{P_{\mathrm{PT}}}}^{+\infty}\left[1-F_{\gamma_{\mathrm{PT,PR}}}(z)\right]f_{Z_{\max}}(z)dz. \tag{13}$$

Substituting (1) and (12) into (13), after some manipulations, we obtain

$$\mathrm{OP}_{\mathrm{P}}=1-\frac{\lambda_{\mathrm{S,PR}}P_{\mathrm{PT}}}{\lambda_{\mathrm{PT,PR}}\theta_{\mathrm{P}}P_{\mathrm{S}}+\lambda_{\mathrm{S,PR}}P_{\mathrm{PT}}}\exp\left(-\frac{\lambda_{\mathrm{PT,PR}}\theta_{\mathrm{P}}\sigma^2}{P_{\mathrm{PT}}}\right)-\frac{\lambda_{\mathrm{R,PR}}P_{\mathrm{PT}}}{\lambda_{\mathrm{PT,PR}}\theta_{\mathrm{P}}P_{\mathrm{R}_b}+\lambda_{\mathrm{R,PR}}P_{\mathrm{PT}}}\exp\left(-\frac{\lambda_{\mathrm{PT,PR}}\theta_{\mathrm{P}}\sigma^2}{P_{\mathrm{PT}}}\right)+\left(\frac{\lambda_{\mathrm{S,PR}}}{P_{\mathrm{S}}}+\frac{\lambda_{\mathrm{R,PR}}}{P_{\mathrm{R}_b}}\right)\exp\left(-\frac{\lambda_{\mathrm{PT,PR}}\theta_{\mathrm{P}}\sigma^2}{P_{\mathrm{PT}}}\right)\times\frac{P_{\mathrm{PT}}}{\lambda_{\mathrm{PT,PR}}\theta_{\mathrm{P}}+\left(\lambda_{\mathrm{S,PR}}/P_{\mathrm{S}}+\lambda_{\mathrm{R,PR}}/P_{\mathrm{R}_b}\right)P_{\mathrm{PT}}}. \tag{14}$$

Next, we propose a simple power allocation for the secondary transmitters to satisfy the QoS of the primary network, i.e., $\mathrm{OP}_{\mathrm{P}}\le\varepsilon_{\mathrm{OP}}$, where $\varepsilon_{\mathrm{OP}}$ is a pre-determined OP value. Now, we observe that if the S-PR distance is longer than the R_b – PR distance, then P_{S} should be higher than P_{R_b}, and vice versa. Hence, we have

$$\frac{P_{\mathrm{S}}}{\lambda_{\mathrm{S,PR}}}=\frac{P_{\mathrm{R}_b}}{\lambda_{\mathrm{R,PR}}}=\chi_1. \tag{15}$$

Substituting (15) into (14), which yields

$$\mathrm{OP}_{\mathrm{P}}=1-\frac{2\mu}{(\alpha_1\chi_1+1)(\alpha_1\chi_1+2)}, \tag{16}$$

where

$$\alpha_1=\frac{\lambda_{\mathrm{PT,PR}}\theta_{\mathrm{P}}}{P_{\mathrm{PT}}},\mu=\exp\left(-\frac{\lambda_{\mathrm{PT,PR}}\theta_{\mathrm{P}}\sigma^2}{P_{\mathrm{PT}}}\right). \tag{17}$$

Solving $\mathrm{OP}_{\mathrm{P}}=\varepsilon_{\mathrm{OP}}$, we can obtain

$$\chi_1=\frac{-3\pm\sqrt{9-4\vartheta}}{2\alpha_1}, \tag{18}$$

where $\vartheta=2-2\mu/(1-\varepsilon_{\mathrm{OP}})$, and $9\ge4\vartheta$.

Because the transmit power P_{S} and P_{R_b} are not negative, we have

$$P_{\mathrm{S}}\le P_{\mathrm{S}}^{*}=\left[\left(\frac{-3+\sqrt{9-4\vartheta}}{2\alpha_1}\right)\lambda_{\mathrm{S,PR}}\right]^{+},\quad P_{\mathrm{R}_b}\le P_{\mathrm{R}_b}^{*}=\left[\left(\frac{-3+\sqrt{9-4\vartheta}}{2\alpha_1}\right)\lambda_{\mathrm{R,PR}}\right]^{+}, \tag{19}$$

where $[x]^{+}=\max(0,x)$.

2.3. IP Constraint

Similar to (4), the instantaneous channel capacity obtained at the eavesdropper (E) at the first and second time slot can be expressed, respectively as

$$C_{\mathrm{S,E}}=\frac{1}{2}\log_2\left(1+\frac{P_{\mathrm{S}}\gamma_{\mathrm{S,E}}}{\kappa_{\mathrm{E}}^2P_{\mathrm{S}}\gamma_{\mathrm{S,E}}+P_{\mathrm{PT}}\gamma_{\mathrm{PT,E}}+\sigma^2}\right),\quad C_{\mathrm{R}_b,\mathrm{E}}=\frac{1}{2}\log_2\left(1+\frac{P_{\mathrm{R}_b}\gamma_{\mathrm{R}_b,\mathrm{E}}}{\kappa_{\mathrm{E}}^2P_{\mathrm{R}_b}\gamma_{\mathrm{R}_b,\mathrm{E}}+P_{\mathrm{PT}}\gamma_{\mathrm{PT,E}}+\sigma^2}\right), \tag{20}$$

where κ_{E}^2 is the total level of hardware impairments of all the eavesdropping links, i.e., $\mathrm{S}\to\mathrm{E}$, $\mathrm{R}_b\to\mathrm{E}$. Moreover, when P_{PT} ? σ^2, we can approximate (20) as

$$C_{\mathrm{S,E}}\approx\frac{1}{2}\log_2\left(1+\frac{P_{\mathrm{S}}\gamma_{\mathrm{S,E}}}{\kappa_{\mathrm{E}}^2P_{\mathrm{S}}\gamma_{\mathrm{S,E}}+P_{\mathrm{PT}}\gamma_{\mathrm{PT,E}}}\right),\quad C_{\mathrm{R}_b,\mathrm{E}}\approx\frac{1}{2}\log_2\left(1+\frac{P_{\mathrm{R}_b}\gamma_{\mathrm{R}_b,\mathrm{E}}}{\kappa_{\mathrm{E}}^2P_{\mathrm{R}_b}\gamma_{\mathrm{R}_b,\mathrm{E}}+P_{\mathrm{PT}}\gamma_{\mathrm{PT,E}}}\right), \tag{21}$$

Moreover, because the RF technique is employed by S and R_b, the intercept probability (IP) can be formulated, similar to [10] as

$$\mathrm{IP}=\Pr\left[\max\left(C_{\mathrm{S,E}},C_{\mathrm{R}_b,\mathrm{E}}\right)\ge C_{\mathrm{S}}\right], \tag{22}$$

where C_{S} is a target rate of the secondary network. Substituting (21) into (22), we obtain (23) as

$$\begin{aligned}\mathrm{IP}&\approx1-\Pr\left(\frac{P_{\mathrm{S}}\gamma_{\mathrm{S,E}}}{\kappa_{\mathrm{E}}^2P_{\mathrm{S}}\gamma_{\mathrm{S,E}}+P_{\mathrm{PT}}\gamma_{\mathrm{PT,E}}}<\rho_{\mathrm{S}},\frac{P_{\mathrm{R}_b}\gamma_{\mathrm{R}_b,\mathrm{E}}}{\kappa_{\mathrm{E}}^2P_{\mathrm{R}_b}\gamma_{\mathrm{R}_b,\mathrm{E}}+P_{\mathrm{PT}}\gamma_{\mathrm{PT,E}}}<\rho_{\mathrm{S}}\right)\\&\approx1-\Pr\left(\gamma_{\mathrm{S,E}}<\frac{P_{\mathrm{PT}}\theta_{\mathrm{E}}}{P_{\mathrm{S}}}\gamma_{\mathrm{PT,E}},\gamma_{\mathrm{R}_b,\mathrm{E}}<\frac{P_{\mathrm{PT}}\theta_{\mathrm{E}}}{P_{\mathrm{R}_b}}\gamma_{\mathrm{PT,E}}\right).\end{aligned} \tag{23}$$

where

$$\rho_{\mathrm{S}}=2\,\hat{}\,(2\mathrm{C}_{\mathrm{S}})-1,\theta_{\mathrm{E}}=\frac{\rho_{\mathrm{S}}}{1-\kappa_{\mathrm{E}}^2\rho_{\mathrm{S}}}. \tag{24}$$

It is noted from (23) that IP = 0 if $1-\kappa_{\mathrm{E}}^2\rho_{\mathrm{S}}\le0$. Hence, in the following, we only consider the case of $1-\kappa_{\mathrm{E}}^2\rho_{\mathrm{S}}>0$. Now, setting $\gamma_{\mathrm{PT,E}}=x$, IP conditioned on x is given as

$$\begin{aligned}\mathrm{IP}(x) &\approx 1-F_{\gamma_{\mathrm{S,E}}}\left(\frac{P_{\mathrm{PT}}\theta_{\mathrm{E}}}{P_{\mathrm{S}}}x\right)F_{\gamma_{\mathrm{R}_b,\mathrm{E}}}\left(\frac{P_{\mathrm{PT}}\theta_{\mathrm{E}}}{P_{\mathrm{R}_b}}x\right)\\ &\approx \exp\left(-\frac{\lambda_{\mathrm{S,E}}P_{\mathrm{PT}}\theta_{\mathrm{E}}}{P_{\mathrm{S}}}x\right)+\exp\left(-\frac{\lambda_{\mathrm{R,E}}P_{\mathrm{PT}}\theta_{\mathrm{E}}}{P_{\mathrm{R}_b}}x\right)\\ &\quad-\exp\left[-\left(\frac{\lambda_{\mathrm{S,E}}}{P_{\mathrm{S}}}+\frac{\lambda_{\mathrm{R,E}}}{P_{\mathrm{R}_b}}\right)P_{\mathrm{PT}}\theta_{\mathrm{E}}x\right].\end{aligned} \quad (25)$$

Then, IP can be approximated by

$$\begin{aligned}\mathrm{IP} &= \int_0^{+\infty}\mathrm{IP}(x)f_{\gamma_{\mathrm{PT,E}}}(x)dx\\ &\approx \frac{\lambda_{\mathrm{PT,E}}}{\lambda_{\mathrm{PT,E}}+\lambda_{\mathrm{S,E}}P_{\mathrm{PT}}\theta_{\mathrm{E}}/P_{\mathrm{S}}}+\frac{\lambda_{\mathrm{PT,E}}}{\lambda_{\mathrm{PT,E}}+\lambda_{\mathrm{R,E}}P_{\mathrm{PT}}\theta_{\mathrm{E}}/P_{\mathrm{R}_b}}\\ &\quad-\frac{\lambda_{\mathrm{PT,E}}}{\lambda_{\mathrm{PT,E}}+\left(\lambda_{\mathrm{S,E}}/P_{\mathrm{S}}+\lambda_{\mathrm{R,E}}/P_{\mathrm{R}_b}\right)P_{\mathrm{PT}}\theta_{\mathrm{E}}}.\end{aligned} \quad (26)$$

Similar to [10], IP must be below a designed value $\varepsilon_{\mathrm{IP}}$, i.e., $\mathrm{IP}\le\varepsilon_{\mathrm{IP}}$. Moreover, similar to (15), we propose a simple power allocation strategy as

$$\frac{P_{\mathrm{S}}}{\lambda_{\mathrm{S,E}}}=\frac{P_{\mathrm{R}_b}}{\lambda_{\mathrm{R,E}}}=\chi_2. \quad (27)$$

Substituting (27) into (26), we obtain (28) as

$$\mathrm{IP}\approx\frac{\chi_2(\chi_2+3\alpha_2)}{(\chi_2+\alpha_2)(\chi_2+2\alpha_2)}, \quad (28)$$

where $\alpha_2=P_{\mathrm{PT}}\theta_{\mathrm{E}}/\lambda_{\mathrm{PT,E}}$.

Using (28) to solve equation $\mathrm{IP}=\varepsilon_{\mathrm{IP}}$, we have

$$\chi_2=\sqrt{\frac{9-\varepsilon_{\mathrm{IP}}}{1-\varepsilon_{\mathrm{IP}}}\frac{\alpha_2}{2}-\frac{3\alpha_2}{2}}. \quad (29)$$

From (29), the transmit powers of the source and the selected relay are constrained as

$$\begin{aligned}P_{\mathrm{S}}\le P_{\mathrm{S}}^{**}&=\left(\sqrt{\frac{9-\varepsilon_{\mathrm{IP}}}{1-\varepsilon_{\mathrm{IP}}}\frac{\alpha_2}{2}-\frac{3\alpha_2}{2}}\right)\lambda_{\mathrm{S,E}},\\ P_{\mathrm{R}_b}\le P_{\mathrm{R}_b}^{**}&=\left(\sqrt{\frac{9-\varepsilon_{\mathrm{IP}}}{1-\varepsilon_{\mathrm{IP}}}\frac{\alpha_2}{2}-\frac{3\alpha_2}{2}}\right)\lambda_{\mathrm{R,E}}.\end{aligned} \quad (30)$$

2.4. Transmit Power and OP Formulation

From (19) and (30), we can give an exact closed-form expression of the transmit power for the source (S) and the selected relay (R_b) as

$$P_{\mathrm{S}}=\min\left(P_{\mathrm{S}}^{*},P_{\mathrm{S}}^{**}\right),P_{\mathrm{R}_b}=\min\left(P_{\mathrm{R}_b}^{*},P_{\mathrm{R}_b}^{**}\right). \quad (31)$$

Next, the instantaneous channel capacity of the $\mathrm{S}\to\mathrm{D}$, $\mathrm{S}\to\mathrm{R}_m$ and $\mathrm{R}_m\to\mathrm{D}$ links can be expressed, respectively as

$$C_{\mathrm{S,D}}=\frac{1}{2}\log_2\left(1+\frac{P_{\mathrm{S}}\gamma_{\mathrm{S,D}}}{\kappa_{\mathrm{D}}^2P_{\mathrm{S}}\gamma_{\mathrm{S,D}}+P_{\mathrm{PT}}\gamma_{\mathrm{PT,D}}+\sigma^2}\right), \quad (32)$$

$$C_{\mathrm{S,R}_m}=\frac{1}{2}\log_2\left(1+\frac{P_{\mathrm{S}}\gamma_{\mathrm{S,R}_m}}{\kappa_{\mathrm{D}}^2P_{\mathrm{S}}\gamma_{\mathrm{S,R}_m}+P_{\mathrm{PT}}\gamma_{\mathrm{PT,R}_m}+\sigma^2}\right), \quad (33)$$

$$C_{\mathrm{R}_m,\mathrm{D}}=\frac{1}{2}\log_2\left(1+\frac{P_{\mathrm{R}_m}\gamma_{\mathrm{R}_m,\mathrm{D}}}{\kappa_{\mathrm{D}}^2P_{\mathrm{R}_m}\gamma_{\mathrm{R}_m,\mathrm{D}}+P_{\mathrm{PT}}\gamma_{\mathrm{PT,D}}+\sigma^2}\right), \quad (34)$$

where κ_{D}^2 is the total level of hardware impairments of all the data links. Then, we can formulate OP of the considered protocol as follows:

$$\begin{aligned}\mathrm{OP}_{\mathrm{S}} &= \Pr(K=0)\Pr\left(C_{\mathrm{S,D}}<C_{\mathrm{S}}\right)\\ &\quad+\sum_{k=1}^{M}C_M^k\Pr(K=k)\underbrace{\Pr\left(C_{\mathrm{S,D}}<C_{\mathrm{S}},C_{\mathrm{R}_m,\mathrm{D}}<C_{\mathrm{S}}\right)}_{I},\end{aligned} \quad (35)$$

where $\Pr(K=k)$ is obtained by

$$\begin{aligned}\Pr(K=k)=\Pr\Big(&C_{\mathrm{S,R}_1}\ge C_{\mathrm{S}},...,C_{\mathrm{S,R}_k}\ge C_{\mathrm{S}},\\ &C_{\mathrm{S,R}_{k+1}}<C_{\mathrm{S}},...,C_{\mathrm{S,R}_M}<C_{\mathrm{S}}\Big).\end{aligned} \quad (36)$$

In case that $k=0$, we have

$$\Pr(K=0)=\Pr\left(C_{\mathrm{S,R}_1}<C_{\mathrm{S}},C_{\mathrm{S,R}_2}<C_{\mathrm{S}},...,C_{\mathrm{S,R}_M}<C_{\mathrm{S}}\right). \quad (37)$$

3. Performance Analysis

In this section, we derive the exact closed-form expression of OP_{S}. At first, we attempt to calculate the probability $\Pr(K=k)$ in (35). By combining (33) and (36), we can write

$$\begin{aligned}\Pr(K=k)=&\prod_{m=1}^{k}\Pr\left(\gamma_{\mathrm{S,R}_m}\ge\omega_1\gamma_{\mathrm{PT,R}_m}+\omega_2\right)\\ &\times\prod_{m=k+1}^{M}\Pr\left(\gamma_{\mathrm{S,R}_m}<\omega_1\gamma_{\mathrm{PT,R}_m}+\omega_2\right).\end{aligned} \quad (38)$$

where

$$\theta_{\mathrm{D}}=\frac{\rho_{\mathrm{S}}}{1-\kappa_{\mathrm{D}}^2\rho_{\mathrm{S}}},\omega_1=\frac{P_{\mathrm{PT}}}{P_{\mathrm{S}}}\theta_{\mathrm{D}},\omega_2=\frac{\sigma^2\theta_{\mathrm{D}}}{P_{\mathrm{S}}}. \quad (39)$$

Furthermore, equation (38) can be expressed as

$$\begin{aligned}&\Pr(K=k)\\ &=\prod_{m=1}^{k}\left[\int_0^{+\infty}\left(1-F_{\gamma_{\mathrm{S,R}_m}}(\omega_1x+\omega_2)\right)f_{\gamma_{\mathrm{PT,R}_m}}(x)dx\right]\\ &\times\prod_{m=k+1}^{M}\left[\int_0^{+\infty}F_{\gamma_{\mathrm{S,R}_m}}(\omega_1x+\omega_2)f_{\gamma_{\mathrm{PT,R}_m}}(x)dx\right].\end{aligned} \quad (40)$$

Substituting (1) into (40), after some manipulations, we obtain (41) as

$$\begin{aligned}\Pr(K=k)=&\left[\frac{\lambda_{\mathrm{PT,R}}}{\lambda_{\mathrm{PT,R}}+\lambda_{\mathrm{S,R}}\omega_1}\exp\left(-\lambda_{\mathrm{S,R}}\omega_2\right)\right]^k\\ &\times\left[1-\frac{\lambda_{\mathrm{PT,R}}}{\lambda_{\mathrm{PT,R}}+\lambda_{\mathrm{S,R}}\omega_1}\exp\left(-\lambda_{\mathrm{S,R}}\omega_2\right)\right]^{M-k}.\end{aligned} \quad (41)$$

Then, when $K=0$, from (41), we have

$$\Pr(K=0)=\left[1-\frac{\lambda_{\mathrm{PT,R}}}{\lambda_{\mathrm{PT,R}}+\lambda_{\mathrm{S,R}}\omega_1}\exp\left(-\lambda_{\mathrm{S,R}}\omega_2\right)\right]^M. \quad (42)$$

Similar to (38)-(41), we can calculate $\Pr\left(C_{\mathrm{S,D}}<C_{\mathrm{S}}\right)$ in (35) exactly as

$$\begin{aligned}\Pr\left(C_{\mathrm{S,D}}<C_{\mathrm{S}}\right)&=\Pr\left(\gamma_{\mathrm{S,D}}<\omega_1\gamma_{\mathrm{PT,D}}+\omega_2\right)\\&=1-\frac{\lambda_{\mathrm{PT,D}}}{\lambda_{\mathrm{PT,D}}+\lambda_{\mathrm{S,D}}\omega_1}\exp\left(-\lambda_{\mathrm{S,D}}\omega_2\right).\end{aligned} \quad (43)$$

Finally, the probability $I=\Pr\left(C_{\mathrm{S,D}}<C_{\mathrm{S}},C_{\mathrm{R}_b,\mathrm{D}}<C_{\mathrm{S}}\right)$ in (35) can be formulated as

$$I=\Pr\left(\gamma_{\mathrm{S,D}}<\omega_1\gamma_{\mathrm{PT,D}}+\omega_2,\gamma_{\mathrm{R}_b,\mathrm{D}}<\omega_3\gamma_{\mathrm{PT,D}}+\omega_4\right), \quad (44)$$

where

$$\omega_3=\frac{P_{\mathrm{PT}}}{P_{\mathrm{R}_b}}\theta_{\mathrm{D}},\omega_4=\frac{\sigma^2\theta_{\mathrm{D}}}{P_{\mathrm{R}_b}}. \quad (45)$$

Setting $\gamma_{\mathrm{PT,D}}=x$, the probability I conditioned on x can be given as

$$I(x)=F_{\gamma_{\mathrm{S,D}}}\left(\omega_1x+\omega_2\right)\times F_{\gamma_{\mathrm{R}_b,\mathrm{D}}}\left(\omega_3x+\omega_4\right). \quad (46)$$

Since $\gamma_{\mathrm{R}_b,\mathrm{D}}=\max\limits_{j=1,2,\ldots,k}\left(\gamma_{\mathrm{R}_j,\mathrm{D}}\right)$, the CDF $F_{\gamma_{\mathrm{R}_b,\mathrm{D}}}\left(\omega_3x+\omega_4\right)$ can be given as

$$\begin{aligned}F_{\gamma_{\mathrm{R}_b,\mathrm{D}}}\left(\omega_3x+\omega_4\right)&=\Pr\left(\gamma_{\mathrm{R}_b,\mathrm{D}}<\omega_3x+\omega_4\right)\\&=\left[1-\exp\left(-\lambda_{\mathrm{R,D}}\left(\omega_3x+\omega_4\right)\right)\right]^k.\end{aligned} \quad (47)$$

Combining (1), (46) and (47), we have

$$\begin{aligned}I(x)&=\left[1-\exp\left(-\lambda_{\mathrm{S,D}}\omega_2\right)\exp\left(-\lambda_{\mathrm{S,D}}\omega_1x\right)\right]\\&\times\sum_{j=0}^{k}\left(-1\right)^jC_k^j\exp\left(-j\lambda_{\mathrm{R,D}}\omega_4\right)\exp\left(-j\lambda_{\mathrm{R,D}}\omega_3x\right)\\&=\sum_{j=0}^{k}\left(-1\right)^jC_k^j\exp\left(-j\lambda_{\mathrm{R,D}}\omega_4\right)\exp\left(-j\lambda_{\mathrm{R,D}}\omega_3x\right)\\&-\sum_{j=0}^{k}\left(-1\right)^jC_k^j\exp\left[-\left(\lambda_{\mathrm{S,D}}\omega_2+j\lambda_{\mathrm{R,D}}\omega_4\right)\right]\\&\times\exp\left[-\left(\lambda_{\mathrm{S,D}}\omega_1+j\lambda_{\mathrm{R,D}}\omega_3\right)x\right].\end{aligned} \quad (48)$$

From (48), the probability I can be calculated as

$$\begin{aligned}I&=\int_0^{+\infty}I(x)f_{\gamma_{\mathrm{PT,D}}}(x)\\&=\sum_{j=0}^{k}\frac{\left(-1\right)^jC_k^j\lambda_{\mathrm{PT,D}}}{\lambda_{\mathrm{PT,D}}+j\lambda_{\mathrm{R,D}}\omega_3}\exp\left(-j\lambda_{\mathrm{R,D}}\omega_4\right)\\&-\sum_{j=0}^{k}\frac{\left(-1\right)^jC_k^j\lambda_{\mathrm{PT,D}}}{\lambda_{\mathrm{PT,D}}+\lambda_{\mathrm{S,D}}\omega_1+j\lambda_{\mathrm{R,D}}\omega_3}\\&\times\exp\left[-\left(\lambda_{\mathrm{S,D}}\omega_2+j\lambda_{\mathrm{R,D}}\omega_4\right)\right].\end{aligned} \quad (49)$$

Finally, substituting (41), (42), (43) and (49) into (35), we obtain an exact closed-form expression of $\mathrm{OP_S}$.

4. Simulation Results

In this section, we present Monte Carlo simulations to verify the theoretical results. In a two-dimensional network, we assume that the co-ordinates of the source, the destination, the relays, the eavesdropper, the primary transmitter, the primary receiver are $(0,0)$, $(1,0)$, $(x_{\mathrm{R}},0)$, $(x_{\mathrm{E}},y_{\mathrm{E}})$, $(0.5,1.5)$ and $(0.5,0.75)$ respectively. In all of the simulations, we fix the path-loss exponent (β) by 3, the variance of AWGN (σ^2) by 1, the required QoS of the primary network $(\varepsilon_{\mathrm{OP}})$ by 0.05, and the target rate of the primary network (C_{P}) by 1.

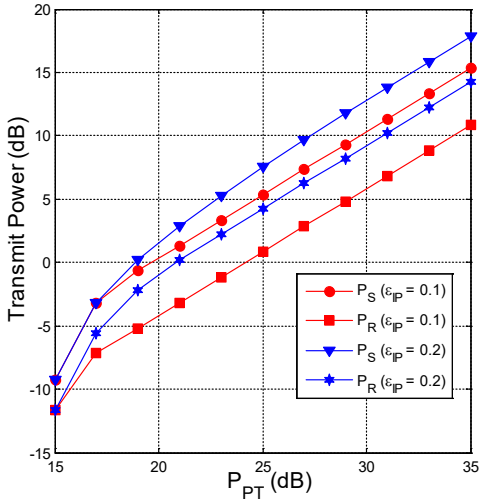

Figure 2. $\mathrm{P_S}$ and $\mathrm{P_R}$ as a function of P_{PT} (dB) when $x_{\mathrm{R}}=0.5$, $x_{\mathrm{E}}=y_{\mathrm{E}}=0.5$, $\kappa_{\mathrm{P}}^2=0.01$, $\kappa_{\mathrm{E}}^2=0.05$, and $C_{\mathrm{S}}=0.25$.

Figure 2 presents the transmit power of the secondary transmitters including source and relays as a function of P_{PT} in dB. As we can see, the transmit powers P_{S} and P_{R} increases as increasing P_{PT}. It is due to the fact that at high transmit power P_{PT}, the QoS of the primary network can be still satisfied with high transmit power of the secondary transmitters. It is also seen from Fig. 2 that the source and the relays can use high transmit power with higher value of $\varepsilon_{\mathrm{IP}}$.

In Fig. 3, we present the outage probability of the primary network $(\mathrm{OP_P})$ and the intercept probability at the eavesdropper (IP) as function of P_{PT} in dB. As shown in Fig. 3, $\mathrm{OP_P}$ and IP are below the values of $\varepsilon_{\mathrm{OP}}$ and $\varepsilon_{\mathrm{IP}}$, respectively, which means that the proposed power allocation not only guarantees the QoS of the primary network but also reduces the intercept possibility of the eavesdropper as expected. It is worth noting that the simulation results (Sim) in Fig. 3 match very well with the theoretical ones (Analysis), which verify our derivations.

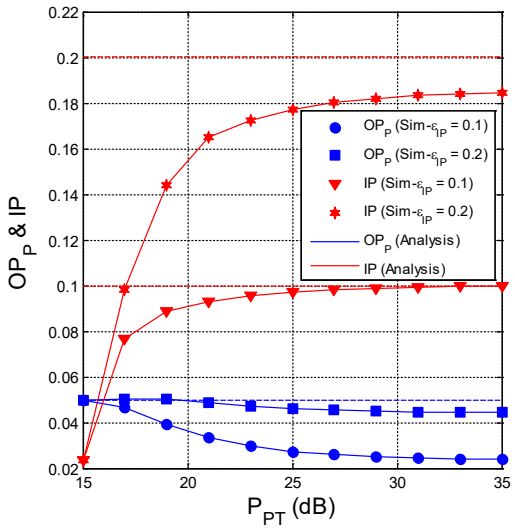

Figure 3. $\mathrm{OP_P}$ and IP as a function of P_{PT} (dB) when $x_{\mathrm{R}} = 0.5,\ x_{\mathrm{E}} = y_{\mathrm{E}} = 0.5,\ \kappa_{\mathrm{P}}^2 = 0.01,\ \kappa_{\mathrm{E}}^2 = 0.05$, and $C_{\mathrm{S}} = 0.25$.

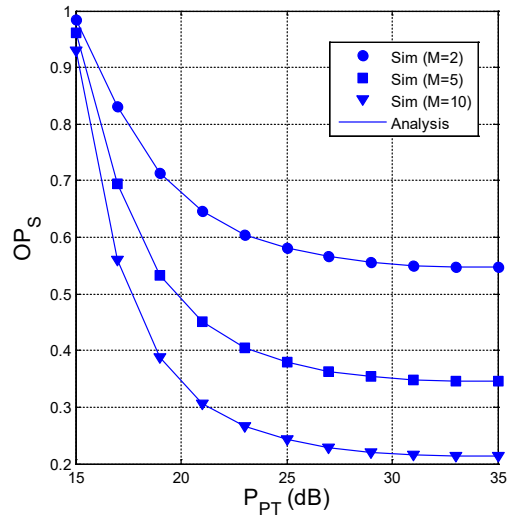

Figure 4. $\mathrm{OP_S}$ as a function of P_{PT} (dB) when $x_{\mathrm{R}} = 0.5,\ x_{\mathrm{E}} = y_{\mathrm{E}} = 0.5,\ \kappa_{\mathrm{P}}^2 = 0.01,\ \kappa_{\mathrm{D}}^2 = \kappa_{\mathrm{E}}^2 = 0.05,\ C_{\mathrm{S}} = 0.25$, and $\varepsilon_{\mathrm{IP}} = 0.25$.

In Fig. 4, we present the outage probability of the secondary network $(\mathrm{OP_S})$ as a function of P_{PT} in dB with different values of M. As seen from this figure, the outage performance of the considered protocol is much better with high number of relays. It is also observed that the $\mathrm{OP_S}$ values decrease with the increasing of P_{PT}. Again, the simulation results verify the theoretical ones.

Figure 5 shows OP of the secondary network $(\mathrm{OP_S})$ as a function of κ_{D}^2 with different positions of the relays. As we can see, the outage performance is worse as the hardware impairment level increases. In addition, we also see that the value of x_{R} also significantly impacts on the outage performance. Indeed, the considered protocol obtains the best and worst performance as $x_{\mathrm{R}} = 0.7$ and $x_{\mathrm{R}} = 0.3$, respectively. Moreover, the gap between the best and worst performance is very high.

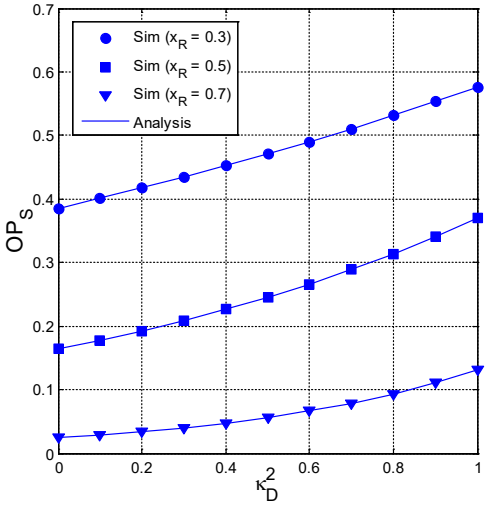

Figure 5. $\mathrm{OP_S}$ as a function of κ_{D}^2 when $P_{\mathrm{PT}} = 25$ (dB), $x_{\mathrm{E}} = y_{\mathrm{E}} = 0.5,\ \kappa_{\mathrm{P}}^2 = 0,\ \kappa_{\mathrm{E}}^2 = 0.3,\ C_{\mathrm{S}} = 0.25,\ M = 15$, and $\varepsilon_{\mathrm{IP}} = 0.25$.

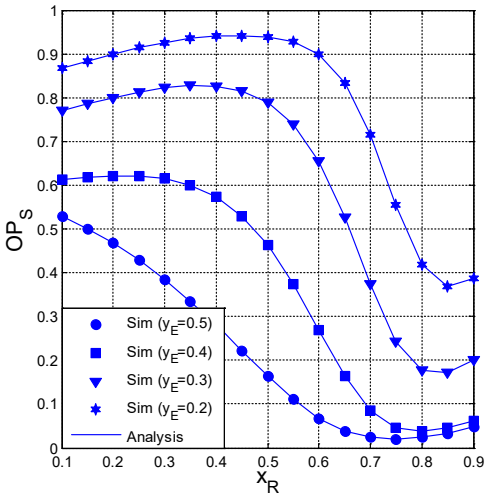

Figure 6. $\mathrm{OP_S}$ as a function of x_{R} when $P_{\mathrm{PT}} = 25$ (dB), $x_{\mathrm{E}} = 0.5,\ \kappa_{\mathrm{P}}^2 = \kappa_{\mathrm{D}}^2 = \kappa_{\mathrm{P}}^2 = 0,\ C_{\mathrm{S}} = 0.25,\ M = 15$, and $\varepsilon_{\mathrm{IP}} = 0.25$.

Figure 6 presents $\mathrm{OP_S}$ as function of x_{R} with different positions of the eavesdropper. We can see that the positions of the relays significantly impact on the value of $\mathrm{OP_S}$. Furthermore, optimal values of x_{R} at which the system obtains the best performance exist. In this figure, it can be seen that the positions of the eavesdropper also affect on the outage performance. Indeed, when the node E is near the secondary transmitters, the OP value is higher, and vice versa.

5. Conclusion

In this paper, we designed the simple and efficient power allocation strategy for the secondary transmitters to satisfy the primary QoS and to control the IP at the eavesdropper. To overcome the limited transmit power issue, and to mitigate the impact of the primary co-channel interference and hardware imperfection, the best-relay selection method was used to enhance the outage performance for the secondary network. Moreover, the performance of the considered protocol was evaluated via both simulation and analysis. The obtained results presented that the outage performance can be enhanced by placing the relays at optimal positions, increasing the number of relays, and equipping the legitimate nodes with good transceiver hardware.

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