Impact of Secondary User Communication on Security Communication of Primary User

Louis Sibomana, Hung Tran, and Quang Anh Tran

Abstract

Recently, spectrum sharing has been considered as a promising solution to improve the spectrum utilization. It however may be vulnerable to security problems as the primary and secondary network access the same resource. Therefore, in this paper, we focus on the performance analysis of a cognitive radio network in the presence of an eavesdropper (EAV) who illegally listens to the primary user (PU) communication in which the transmit power of the secondary transmitter (SU-Tx) is subject to the joint constraint of peak transmit power of the SU-Tx and outage probability of the PU. Accordingly, an adaptive transmit power policy and an analytical expression of symbol error probability are derived for the SU. Most importantly, security evaluations of primary network in terms of the probability of existence of non-zero secrecy capacity and outage probability of secrecy capacity are obtained. Numerical results reveal a fact that the security of the primary network does not only depends on the channel mean powers between primary and secondary networks, but also strongly depends on the channel condition of the SU-Tx \rightarrow EAV link and transmit power policy of the SU-Tx.

Index Terms

Cognitive radio network; symbol error probability; secrecy capacity; secrecy outage probability.

I. INTRODUCTION

Recently, cognitive radio network (CRN) has been considered as a feasible solution in improving the spectrum utilization [1]–[3] in which the spectrum underlay approach, one of spectrum

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access techniques in CRN, has received a lot attention in academia [4], [5]. In particular, in underlay CRN, the secondary user (SU) is allowed to simultaneously access the licensed spectrum of the primary user (PU) as long as the inflicted interference at the PU is kept below a predefined threshold [2]–[4]. To protect the communication of the PU, different constraints such as outage constraint, peak or average interference power constraints, and power allocation strategies for the SU have been studied [6]–[8]. By doing so, the spectrum utilization have been improved significantly. Even though, spectrum underlay approach may reveal disadvantages in security issues of both secondary and primary networks. This is due to the broadcast nature of wireless signals.

Generally, secure communication of wireless networks is typically achieved by using cryptographic protocols above the physical layer, but the signal may be decoded at the physical layer. As a consequence, information theoretic security at the physical layer has become one of the most concerned topics in wireless communication. More specifically, the problem of secure transmission was studied from an information theoretic perspective for a wiretap channel [9]. The aim of information theoretic security is to provide a measurement that how much information can be transmitted safely by exploiting the physical characteristics of the wireless channel with the existence of eaversdropper (EAV) [10]-[13]. In [11], [12], a secrecy capacity concept has been introduced to evaluate the security level of transmitted messages as there exists an EAV, i.e., the secrecy capacity is defined as the maximum transmission rate at which a message can be reliably received by the legitimate receiver but kept perfectly secret from the EAV. This performance metric, i.e., ergodic capacity is suitable for delay tolerant applications. Otherwise, the outage probability of secrecy capacity is suitable for delay-limited information applications [10], [11]. In a spectrum sharing CRN, SU and PU share the same frequency band, they may cause mutual interference as a missed power control or missed detection happen. Hence, the security in CRN becomes more challenging. In [14], authors have presented an overview on several existing security attacks to the physical layer in CRN, and then the secrecy capacity and outage probability of secrecy capacity of the PU have been analyzed. Most recently, an information theoretic secrecy for device-to-device (D2D) communication in cellular network has been considered in [15]. Analytical results have illustrated that the D2D communication is known as the interference source to the EAV which can improve the secrecy capacity for the considered system. In [16], authors have considered an information secrecy cooperative game

where the PU and SU cooperate and adjust their transmit powers to maximize the secrecy and information rates. In this context, the cooperation is adopted when the PU achieves higher secrecy rate with the help of the SU. Otherwise, the PU does not cooperate with the SU. However, [14], [16] did not consider the interference constraints of the SU. As a result, the quality of service (QoS) of primary network is not guaranteed due to the interference from the SU transmission. Following the concerns of security for CRN, we have investigated the probability of existence of non-zero secrecy capacity for the PU where the SU transmit power control is subject to the maximum acceptable PU outage constraint and the peak transmit power of the SU [17]. However, the mathematical approach is rather complex and it is impossible to analyze further.

To get rid of mathematical complexity in [17] and differ from the aforementioned works, in this paper, we use another mathematic approach to analyze the system performance and security. In particular, it is assumed that the secondary transmitter (SU-Tx) transmit power is subject to the joint constraint of the PU outage and SU maximum transmit power limit. Accordingly, the power allocation policy for the SU-Tx, the probability density function (PDF), and cumulative distribution function (CDF) for the signal-to-interference-plus-noise ratio (SINR) are obtained. On this basis, we do not only analyze the probability of existence of non-zero secrecy capacity for the PU but also the outage probability of the secrecy capacity of the PU. Furthermore, the performance of secondary network, which is subject to the interference from the PU, in terms of the symbol error probability (SEP) is analyzed. The numerical results indicate that the probability of existence of non-zero secrecy capacity of the PU strongly depend on the channel conditions of the SU-Tx to the EAV link and SU-Tx adaptive transmit power policy. Most interestingly, the security of the PU can be improved by the interference from the SU-Tx to the EAV. To the best of our knowledge, there is no previous publication addressing on this problem.

The remainder of this paper is organized as follows. In Section II, the system and channel model and assumptions are introduced. Section III derives the SU-Tx transmit power policy, the CDF and the PDF of the received SINR. In Section IV, the SU SEP, the PU probability of existence of non-zero secrecy capacity and outage probability of the secrecy capacity are analyzed. In Section V, numerical results and discussion are provided. Finally, conclusions are presented in Section VI.

II. SYSTEM AND CHANNEL MODEL

Let us consider a CRN model as shown in Fig. 1 in which the SU-Tx utilizes the licensed frequency band of the PU to communicate with the secondary receiver (SU-Rx) receiver. There exists an EAV who is capable of eavesdropping the signal sent by the primary transmitter (PU-Tx) by observing the channel output. Intuitively, we can see that the SU-Tx and PU-Tx can cause mutual interference to the primary receiver (PU-Rx) and SU-Rx, respectively. The considered system is a typical model of the D2D communication where the SU-Tx \rightarrow SU-Rx link corresponds to the D2D link while PU-Tx \rightarrow PU-Rx link is an instance of uplink or downlink in the cellular network [18]. On the basis of Shannon theorem, the channel capacity between the PU-Tx and PU-Rx under interference caused by the SU-Tx is formulated by

$$C_P = B \log_2\left(1 + \gamma_{\rm P}\right) \tag{1}$$

where B is system bandwidth and $\gamma_{\rm P}$ is the SINR at the PU-Rx defined by

$$\gamma_{\rm P} = \frac{P_{\rm p}h}{P_{\rm s}\alpha + N_0} \tag{2}$$

while P_p , P_s , and N_0 are the transmit powers of the PU-Tx, SU-Tx, and noise power, respectively. Further, symbols h and α denote the channel power gains of the PU-Tx \rightarrow PU-Rx communication link and the SU-Tx \rightarrow PU-Rx interference link, respectively. Similarly, the capacity between the SU-Tx and SU-Rx under interference caused by the PU-Tx can be expressed as

$$C_S = B \log_2 \left(1 + \gamma_S \right) \tag{3}$$

where $\gamma_{\rm S}$ is the SINR at the SU-Rx which is formulated as

$$\gamma_{\rm S} = \frac{P_{\rm s}g}{P_{\rm p}\beta + N_0} \tag{4}$$

here, g and β are channel power gains for the SU-Tx \rightarrow SU-Rx communication link and PU-Tx \rightarrow SU-Rx interference link, respectively. Due to the nature of broadcast signal in the wireless communication, the EAV may eavesdrop the transmitted information from the PU-Tx to the PU-Rx. However, the received information at the EAV is also subject to the interference caused by the SU-Tx. Thus, the capacity between the PU-Tx and EAV over the wire-tap channel is presented as

$$C_E = B \log_2 \left(1 + \gamma_E \right) \tag{5}$$

where γ_E is the SINR at the EAV and defined as

$$\gamma_E = \frac{P_{\rm p}f}{P_{\rm s}\varphi + N_0} \tag{6}$$

In (6), f and φ are, respectively, channel power gains of the PU-Tx \rightarrow EAV and SU-Tx \rightarrow EAV links.

In this work, the channels are assumed to be block Rayleigh fading, i.e., the channel remains constant over one time slot, and may change independently from one slot to the next. This assumption is widely accepted in realistic models for wireless communications and is applicable for severe shadowing environment where the line-of-sight does not exist such as in crowed city with many high buildings. Moreover, we denote Ω_X as the channel mean gain where $X \in \{g, h, f, \alpha, \beta, \varphi\}$, i.e., the channel mean gains are non-identical. This is reasonable since users may be located at different positions. Accordingly, the channel power gains are independent but not necessarily identically distributed (i.n.i.d.) random variables (RVs) with exponential distribution given as follows:

$$f_X(x) = \frac{1}{\Omega} \exp\left(-\frac{x}{\Omega}\right) \tag{7}$$

$$F_X(x) = 1 - \exp\left(-\frac{x}{\Omega}\right) \tag{8}$$

where $f_X(x)$ and $F_X(x)$ are the PDF and CDF of the RV X, respectively.

A. Spectrum sharing constraints

Given the considered system model, the SU try to utilize the licensed frequency band of the PU for its communication, however this operation may cause unpredictable effects to the QoS of the PU and it is an unacceptable issue in the PU's view. In order to not cause harmful interference to the PU-Rx, the interference constraints given by the PU should be established, and the SU needs to have an appropriate power allocation policy to keep interference at the PU-Rx below a predefined threshold. In the light of this idea, the interference constraint given by the PU can be interpreted into the outage probability constraint as [6]

$$P_{\text{out}}^P = \Pr\{B \log_2(1+\gamma_P) < r_p\} \le \theta_{th}$$
(9)

where r_p and θ_{th} are, respectively, the primary network target transmission rate and outage probability threshold. The equation (9) can interpret by words that the SU-Tx is allowed to

access the licensed frequency band of the PU and cause limited interference to the PU as long as the outage probability of the PU capacity is kept below a predefined threshold, θ_{th} . Furthermore, the transmit power is limited in reality, thus the SU-Tx transmit power is subject to additional constraint, named as the peak transmit power or maximum transmit power limit, as

$$P_{\rm s} \le P_{\rm pk} \tag{10}$$

B. Performance Metrics

Based on the transmit power constraint given by the PU and SU, our aim of this paper is to investigate the system performance of CRN by calculating the SU SEP and analyze the impact of the presence of the SU on the security communication of the PU.

1) Symbol Error Probability: According to [19], the SEP of the SU is characterized as

$$P_e = \frac{\epsilon \sqrt{\eta}}{2\sqrt{\pi}} \int_0^\infty F_{\gamma_{\rm S}}(\gamma) \frac{\exp\left(-\eta\gamma\right)}{\sqrt{\gamma}} d\gamma \tag{11}$$

where ϵ and η are constants which depends on the particular modulation scheme. For example, for *M*-phase shift keying (M - PSK) modulation scheme, $\epsilon = 2$ and $\eta = \sin^2(\pi/M)$.

2) Probability of Existence of a Non-zero Secrecy Capacity: To analyze the secure communication of the PU under the interference from the SU, we employed the instantaneous secrecy capacity. According to results reported in [10], the secrecy capacity of the primary communication is formulated as

$$C_{\text{sec}} = \begin{cases} B \log_2(1+\gamma_{\text{P}}) - B \log_2(1+\gamma_{\text{E}}), & \gamma_{\text{P}} \ge \gamma_{\text{E}} \\ 0, & \gamma_{\text{P}} < \gamma_{\text{E}} \end{cases}$$
(12)

Accordingly, the probability of existence of a non-zero secrecy capacity of the PU is expressed as

$$P_{\text{ex}} = \Pr\left\{C_{\text{sec}} > 0\right\} = \Pr\left\{\gamma_P > \gamma_E\right\}$$
(13)

3) Outage Probability of Secrecy Capacity: The outage probability of secrecy capacity is defined as the probability that the instantaneous secrecy capacity is less than a secrecy target rate $R_s > 0$. Thus, the outage probability of secrecy capacity for the primary network is given by

$$P_{\text{out,sec}} = \Pr\left\{C_{\text{sec}} < R_s\right\} \tag{14}$$

According to [20, Eq.(6)], this performance metric can be expanded by using the total probability theorem as

$$P_{\text{out,sec}} = \Pr\{C_{\text{sec}} < R_s | \gamma_P > \gamma_E\} \Pr\{\gamma_P > \gamma_E\} + \Pr\{C_{\text{sec}} < R_s | \gamma_P \le \gamma_E\} \Pr\{\gamma_P \le \gamma_E\}$$
(15)

III. STATISTICS FUNCTIONS

In this section, we derive the power allocation policy for the SU. Thereafter, the CDF and PDF for different SINR are obtained. Let us commence by deriving the CDF and PDF of a function of RVs which are important to analyze the system performance in next subsections.

Lemma 1: Assuming that a and b are positive constants while X_1 and X_2 are independent exponentially distributed RVs with mean values Ω_1 and Ω_2 , respectively. A RV Z is defined by

$$Z = \frac{aX_1}{bX_2 + 1} \tag{16}$$

The CDF and PDF of Z are formulated, respectively, as follows:

$$F_Z(z) = 1 - \frac{1}{1 + z \frac{b\Omega_2}{a\Omega_1}} \exp\left(-\frac{z}{a\Omega_1}\right)$$
(17)

$$f_Z(z) = \frac{b\Omega_2}{a\Omega_1} \frac{\exp\left(-\frac{z}{a\Omega_1}\right)}{\left(1 + z\frac{b\Omega_2}{a\Omega_1}\right)^2} + \frac{\exp\left(-\frac{z}{a\Omega_1}\right)}{a\Omega_1\left(1 + z\frac{b\Omega_2}{a\Omega_1}\right)}$$
(18)

Proof: According to the probability definition, the CDF of the RV Z can be derived by using the same approach [21, Eq.(14)] as follows

$$F_Z(z) = \Pr\{Z < z\} = \int_0^\infty \Pr\{X_1 < \frac{z(bx+1)}{a}\} f_{X_2}(x)dx$$
(19)

As X_1 and X_2 are independent exponentially distributed RVs, the equation (19) can be rewritten as follows

$$F_Z(z) = \int_0^\infty \left\{ 1 - \exp\left[-\frac{z(bx+1)}{a\Omega_1}\right] \right\} \frac{1}{\Omega_2} \exp\left(-\frac{x}{\Omega_2}\right) dx$$
(20)

After integration, the CDF of Z is obtained as in (17). Then, by differentiating (17) with respect to z, we obtain the PDF of Z as shown in (18).

A. Power Allocation Policy of the SU-Tx

As the SU accesses the licensed frequency band of the PU, the SU-Tx must have a flexible transmit power policy to keep the interference of the PU below a predetermined threshold. From (9), we derive the outage probability of the PU to withdraw the transmit power expression of the SU as

$$P_{\rm out}^{\rm P} = \Pr\left\{\frac{P_{\rm p}h}{P_{\rm s}\alpha + N_0} < \gamma_{th}\right\}$$
(21)

where $\gamma_{th} = 2^{\frac{r_p}{B}} - 1$. Using the Lemma 1, an expression for the PU outage probability is presented as

$$P_{\rm out}^{\rm P} = 1 - \frac{P_{\rm p}\Omega_h}{\gamma_{th}P_{\rm s}\Omega_\alpha + P_{\rm p}\Omega_h} \exp\left(-\frac{N_0\gamma_{th}}{P_{\rm p}\Omega_h}\right)$$
(22)

Substituting (22) into (9) and then combining with (10) yields an adaptive transmit power policy of the SU-Tx as

$$\mathcal{P} = \min\left\{\frac{P_{\mathbf{p}}\Omega_{h}}{\gamma_{th}\Omega_{\alpha}}\chi^{+}, P_{\mathbf{pk}}\right\}$$
(23)

where

$$\chi^{+} = \max\left\{\frac{1}{1-\theta_{th}}\exp\left(-\frac{N_{0}\gamma_{th}}{P_{p}\Omega_{h}}\right) - 1, 0\right\}$$
(24)

In what follows, the SU-Tx uses the power allocation policy given in (23) to transmit the signal to the SU-Rx.

B. Statistics for SINRs

By looking into the considered performance metrics given in (11), (13), and (15), we can see that the CDF and PDF for SINRs are important functions to analyze the system performance. Therefore, we derive these functions as follows:

Using the power allocation policy given in (23) and setting $c = \frac{P_p}{N_0}$ and $d = \frac{P}{N_0}$ as the signal-to-noise ratios (SNRs), the SINRs at the SU-Rx, PU-Rx, and EAV given respectively in (4), (2), and (6) are rewritten as

$$\gamma_{\rm P} = \frac{ch}{d\alpha + 1} \tag{25}$$

$$\gamma_{\rm E} = \frac{cf}{d\varphi + 1} \tag{26}$$

$$\gamma_{\rm S} = \frac{dg}{c\beta + 1} \tag{27}$$

1) CDF and PDF of γ_P : Using Lemma 1, the CDF and PDF of γ_P can be obtained by setting $a = c, b = d, \Omega_1 = \Omega_h$ and $\Omega_2 = \Omega_\alpha$ as follows:

$$F_{\gamma_P}(x) = 1 - \frac{1}{1 + xA_0} \exp\left(-\frac{x}{B_0}\right)$$
(28)

$$f_{\gamma_P}(x) = \exp\left(-\frac{x}{B_0}\right) \left[\frac{A_0}{\left(1 + A_0 x\right)^2} + \frac{1}{B_0 \left(1 + A_0 x\right)}\right]$$
(29)

where $A_0 = \frac{d\Omega_{\alpha}}{c\Omega_h}$ and $\frac{1}{B_0} = \frac{1}{c\Omega_h}$.

2) CDF and PDF of γ_E : Similarly, the CDF and PDF of γ_E are, respectively, obtained by setting a = c, b = d, $\Omega_1 = \Omega_f$ and $\Omega_2 = \Omega_{\varphi}$ as

$$F_{\gamma_E}(y) = 1 - \frac{1}{1 + yD_0} \exp\left(-\frac{y}{E_0}\right)$$
(30)

$$f_{\gamma_E}(y) = \exp\left(-\frac{y}{E_0}\right) \left[\frac{D_0}{\left(1 + D_0 y\right)^2} + \frac{1}{E_0 \left(1 + D_0 y\right)}\right]$$
(31)

where $D_0 = \frac{d\Omega_{\varphi}}{c\Omega_f}$ and $\frac{1}{E_0} = \frac{1}{c\Omega_f}$.

3) CDF and PDF of γ_s : By setting a = d, b = c, $\Omega_1 = \Omega_g$ and $\Omega_2 = \Omega_\beta$, we also obtain the CDF and PDF of γ_s as

$$F_{\gamma_S}(u) = 1 - \frac{1}{1 + uF_0} \exp\left(-\frac{u}{G_0}\right)$$
(32)

$$f_{\gamma_S}(u) = \exp\left(-\frac{u}{G_0}\right) \left[\frac{F_0}{\left(1 + F_0 u\right)^2} + \frac{1}{G_0\left(1 + F_0 u\right)}\right]$$
(33)

where $F_0 = \frac{c\Omega_\beta}{d\Omega_g}$ and $\frac{1}{G_0} = \frac{1}{d\Omega_g}$.

IV. PERFORMANCE ANALYSIS

In this section, adopting the obtained transmit power policy given in (23), the SEP of the SU, analytical expressions for the probability of existence of non-zero secrecy capacity, and outage probability of secrecy capacity of the primary network are derived.

A. Symbol Error Probability of the SU

By substituting (32) into (11), an expression of the SU SEP can be presented as

$$P_e = \underbrace{\underbrace{\frac{\epsilon\sqrt{\eta}}{2\sqrt{\pi}}\int_{0}^{\infty}\frac{\exp\left(-\eta\gamma\right)}{\sqrt{\gamma}}d\gamma}_{H_1} - \underbrace{\frac{\epsilon\sqrt{\eta}}{2\sqrt{\pi}}\int_{0}^{\infty}\frac{1}{(1+F_0\gamma)\sqrt{\gamma}}\exp\left(-\frac{\gamma}{F_1}\right)d\gamma}_{H_2} \tag{34}$$

where $\frac{1}{F_1} = \frac{1}{G_0} + \eta$. Moreover, using [22, Eq. (3.361.2)], H_1 is given by

$$H_1 = \frac{\epsilon}{2} \tag{35}$$

Furthermore, by changing variable and setting $t = \gamma + \frac{1}{F_0}$, H_2 is obtained as

$$H_{2} = \frac{\epsilon \sqrt{\eta}}{2\sqrt{\pi}} \frac{1}{F_{0}} \exp\left(\frac{1}{F_{0}F_{1}}\right) \int_{\frac{1}{F_{0}}}^{\infty} \frac{1}{t\sqrt{t-\frac{1}{F_{0}}}} \exp\left(-\frac{t}{F_{1}}\right) dt$$
$$= \frac{\epsilon}{2} \sqrt{\frac{\eta\pi}{F_{0}}} \exp\left(\frac{1}{F_{0}F_{1}}\right) \left[1 - \mathcal{Q}\left(\frac{1}{\sqrt{F_{0}F_{1}}}\right)\right]$$
(36)

where (36) is solved with the help of [22, Eq. (3.363.2)] and $Q(\cdot)$ is the error function defined as $Q(z) = (2/\sqrt{\pi}) \int_{0}^{z} \exp(-t^2) dt$. As a consequence, the analytical expression of the SU SEP is given by

$$P_e = \frac{\epsilon}{2} - \frac{\epsilon}{2} \sqrt{\frac{\eta \pi}{F_0}} \exp\left(\frac{1}{F_0 F_1}\right) \left[1 - \mathcal{Q}\left(\frac{1}{\sqrt{F_0 F_1}}\right)\right]$$
(37)

B. Analysis of Secure Communication of the PU

In this subsection, analytical expressions of the probability of existence of non-zero secrecy capacity and outage probability of secrecy capacity of the PU are obtained.

1) Probability of Existence of Secrecy Capacity: According to the margin probability definition, we can derive the probability of existence of non-zero secrecy capacity for the PU given in (13) as follows:

$$P_{\text{ex}} = 1 - \int_{0}^{\infty} \Pr\left\{\gamma_{\text{P}} < y\right\} f_{\gamma_{\text{E}}}(y) dy = 1 - \int_{0}^{\infty} \frac{1}{1 + yA_{0}} \exp\left(-\frac{y}{B_{0}}\right) f_{\gamma_{\text{E}}}(y) dy$$
$$= D_{0} \int_{0}^{\infty} \frac{\exp\left[-\left(\frac{1}{B_{0}} + \frac{1}{E_{0}}\right)y\right]}{(1 + yA_{0})\left(1 + D_{0}y\right)^{2}} dy + \frac{1}{E_{0}} \int_{0}^{\infty} \frac{\exp\left[-\left(\frac{1}{B_{0}} + \frac{1}{E_{0}}\right)y\right]}{(1 + A_{0}y)\left(1 + yD_{0}\right)} dy$$
(38)

where $f_{\gamma_{\rm E}}(y)$ is given in (31). By setting $\frac{1}{C_0} = \frac{1}{B_0} + \frac{1}{E_0}$, we can rewrite (38) as

$$P_{\text{ex}} = \underbrace{D_0 \int_0^\infty \frac{\exp\left(-\frac{y}{C_0}\right)}{\left(1 + yA_0\right) \left(1 + D_0y\right)^2} dy}_{I_1} + \underbrace{\frac{1}{E_0} \int_0^\infty \frac{\exp\left(-\frac{y}{C_0}\right)}{\left(1 + A_0y\right) \left(1 + yD_0\right)} dy}_{I_2} \tag{39}$$

Moreover, I_1 and I_2 can be solved as follows:

• If $A_0 = D_0$, the integrals I_1 and I_2 can be calculated with the help of [22, Eq. (3.353.2)] and [22, Eq.(3.353.3)], respectively, as

$$I_1 = D_0 \int_0^\infty \frac{\exp\left[-\frac{y}{C_0}\right]}{\left(1 + yD_0\right)^3} dy = \frac{C_0 D_0 - 1}{2C_0 D_0} + \frac{1}{2C_0^2 D_0^2} \exp\left(\frac{1}{C_0 D_0}\right) \Gamma\left[0, \frac{1}{C_0 D_0}\right]$$
(40)

$$I_{2} = \frac{1}{E_{0}} \int_{0}^{\infty} \frac{\exp\left[-\frac{y}{C_{0}}\right]}{\left(1 + D_{0}y\right)^{2}} dy = \frac{1}{E_{0}D_{0}} + \frac{1}{C_{0}D_{0}^{2}E_{0}} \exp\left(\frac{1}{C_{0}D_{0}}\right) \operatorname{Ei}\left(-\frac{1}{C_{0}D_{0}}\right)$$
(41)

where $\operatorname{Ei}(z) = -\int_{-z}^{\infty} \frac{e^{-t}}{t} dt$ is the exponential integral and $\Gamma[0, z] = -\operatorname{Ei}(-z)$ for z > 0 is the incomplete gamma function.

• If $A_0 \neq D_0$, I_1 is derived as

$$I_{1} = \underbrace{\frac{A_{0}^{2}D_{0}}{(D_{0} - A_{0})^{2}} \int_{0}^{\infty} \frac{\exp\left(-\frac{y}{C_{0}}\right)}{1 + A_{0}y} dy}_{I_{11}} + \underbrace{\frac{D_{0}^{2}}{D_{0} - A_{0}} \int_{0}^{\infty} \frac{\exp\left(-\frac{y}{C_{0}}\right)}{(1 + D_{0}y)^{2}} dy}_{I_{12}}}_{I_{12}} - \underbrace{\frac{A_{0}D_{0}^{2}}{(D_{0} - A_{0})^{2}} \int_{0}^{\infty} \frac{\exp\left(-\frac{y}{C_{0}}\right)}{1 + D_{0}y} dy}_{I_{13}}}_{I_{13}}$$
(42)

where the integrals I_{11} and I_{13} are solved using [22, Eq. (3.352.4)] as

$$I_{11} = \frac{A_0 D_0}{(D_0 - A_0)^2} \exp\left(\frac{1}{A_0 C_0}\right) \Gamma\left[0, \frac{1}{A_0 C_0}\right]$$
(43)

$$I_{13} = \frac{A_0 D_0}{(D_0 - A_0)^2} \exp\left(\frac{1}{C_0 D_0}\right) \Gamma\left[0, \frac{1}{C_0 D_0}\right]$$
(44)

Furthermore, with the help of [22, Eq.(3.353.3)], we obtain an expression for I_{12} as

$$I_{12} = \frac{D_0}{D_0 - A_0} + \frac{1}{C_0(D_0 - A_0)} \exp\left(\frac{1}{C_0 D_0}\right) \operatorname{Ei}\left[-\frac{1}{C_0 D_0}\right]$$
(45)

In addition, when $A_0 \neq D_0$, I_2 is calculated as

$$I_{2} = \underbrace{\frac{A_{0}}{E_{0}(A_{0} - D_{0})} \int_{0}^{\infty} \frac{\exp\left[-\frac{y}{C_{0}}\right]}{1 + A_{0}y} dy}_{I_{21}} - \underbrace{\frac{D_{0}}{E_{0}(A_{0} - D_{0})} \int_{0}^{\infty} \frac{\exp\left[-\frac{y}{C_{0}}\right]}{1 + D_{0}y} dy}_{I_{22}}}_{I_{22}}$$
(46)

where the expressions of I_{21} and I_{22} are obtained as

$$I_{21} = \frac{1}{E_0(A_0 - D_0)} \exp\left(\frac{1}{A_0 C_0}\right) \Gamma\left[0, \frac{1}{A_0 C_0}\right]$$
(47)

$$I_{22} = \frac{1}{E_0(A_0 - D_0)} \exp\left(\frac{1}{C_0 D_0}\right) \Gamma\left[0, \frac{1}{C_0 D_0}\right]$$
(48)

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Finally, we obtain an analytical expression of probability of existence of secrecy capacity of the PU as

• For $A_0 = D_0$,

$$P_{\text{ex}} = \frac{C_0 D_0 - 1}{2C_0 D_0} + \frac{1}{D_0 E_0} + \frac{1}{2C_0^2 D_0^2} \exp\left(\frac{1}{C_0 D_0}\right) \Gamma\left[0, \frac{1}{C_0 D_0}\right] + \frac{1}{C_0 D_0^2 E_0} \exp\left(\frac{1}{C_0 D_0}\right) \text{Ei}\left(-\frac{1}{C_0 D_0}\right)$$
(49)

• For $A_0 \neq D_0$,

$$P_{\text{ex}} = \frac{A_0 D_0}{\left(D_0 - A_0\right)^2} \left\{ \exp\left(\frac{1}{A_0 C_0}\right) \Gamma\left[0, \frac{1}{A_0 C_0}\right] - \exp\left(\frac{1}{C_0 D_0}\right) \Gamma\left[0, \frac{1}{C_0 D_0}\right] \right\} + \frac{D_0}{D_0 - A_0} + \frac{1}{C_0 (D_0 - A_0)} \exp\left(\frac{1}{C_0 D_0}\right) \text{Ei}\left(-\frac{1}{C_0 D_0}\right) + \frac{1}{E_0 (A_0 - D_0)} \left\{ \exp\left(\frac{1}{A_0 C_0}\right) \Gamma\left[0, \frac{1}{A_0 C_0}\right] - \exp\left(\frac{1}{C_0 D_0}\right) \Gamma\left[0, \frac{1}{C_0 D_0}\right] \right\}$$
(50)

2) *Outage Probability of Secrecy Capacity:* The probability of outage of the secrecy capacity of the PU in (15) can be rewritten as

$$P_{\text{out,sec}} = \underbrace{\Pr\{C_{\text{sec}} < R_s | \gamma_P > \gamma_E\}}_{J_1} \Pr\{\gamma_P > \gamma_E\}$$
$$+ \underbrace{\Pr\{C_{\text{sec}} < R_s | \gamma_P \le \gamma_E\}}_{J_2} \Pr\{\gamma_P \le \gamma_E\}}_{J_2}$$
(51)

where $\Pr{\{\gamma_P > \gamma_E\}} = P_{ex}$ and $\Pr{\{C_{sec} < R_s | \gamma_P \le \gamma_E\}} = 1$ since $R_s > 0$. Accordingly, J_2 is given by

$$J_2 = \Pr\{\gamma_P \le \gamma_E\} = 1 - \Pr\{\gamma_P > \gamma_E\} = 1 - P_{\text{ex}}$$
(52)

Furthermore, we derive J_1 by using the Bayes's law as follows:

$$J_{1} = \Pr\left\{\frac{1+\gamma_{\rm P}}{1+\gamma_{\rm E}} < \xi, \gamma_{\rm P} > \gamma_{\rm E}\right\} = \int_{0}^{\infty} \int_{y}^{\xi(1+y)-1} f_{\gamma_{\rm P}}(x) f_{\gamma_{\rm E}}(y) dx dy$$
$$= \underbrace{\int_{0}^{\infty} F_{\gamma_{\rm P}}\left(\xi(1+y)-1\right) f_{\gamma_{\rm E}}(y) dy}_{J_{11}} - \underbrace{\int_{0}^{\infty} F_{\gamma_{\rm P}}(y) f_{\gamma_{\rm E}}(y) dy}_{J_{12}}$$
(53)

where $\xi = 2^{\frac{R_s}{B}}$. Substituting (28) into (53), we have

$$J_{11} = \int_{0}^{\infty} \left[1 - \frac{1}{1 + A_0[\xi(1+y) - 1]} \exp\left(-\frac{\xi(1+y) - 1}{B_0}\right) \right] f_{\gamma_{\rm E}}(y) dy$$
$$= 1 - \underbrace{\frac{\exp\left(-\frac{\xi - 1}{B_0}\right)}{1 + A_0(\xi - 1)} \int_{0}^{\infty} \frac{\exp\left(-\frac{\xi}{B_0}y\right)}{1 + \frac{A_0\xi}{1 + A_0(\xi - 1)}y} f_{\gamma_{\rm E}}(y) dy}_{J_{111}}$$
(54)

where again $f_{\gamma_E}(y)$ is given in (31) and

$$J_{12} = \int_{0}^{\infty} F_{\gamma_{P}}(y) f_{\gamma_{E}}(y) dy = \Pr\{\gamma_{P} < \gamma_{E}\} = 1 - P_{ex}$$
(55)

Moreover, by setting $A_1 = \frac{\exp\left(-\frac{\xi-1}{B_0}\right)}{1+A_0(\xi-1)}$ and $D_1 = \frac{A_0\xi}{1+A_0(\xi-1)}$ in (54), we can rewrite J_{111} as

$$J_{111} = A_1 \int_{0}^{\infty} \frac{\exp\left(-\frac{\xi}{B_0}y\right)}{1+D_1 y} \left[\frac{D_0 \exp\left(-\frac{y}{E_0}\right)}{(1+D_0 y)^2} + \frac{\exp\left(-\frac{y}{E_0}\right)}{E_0(1+D_0 y)}\right] dy$$
$$= A_1 D_0 \int_{0}^{\infty} \frac{\exp\left(-\frac{y}{B_1}\right)}{(1+D_1 y)(1+D_0 y)^2} dy + \frac{A_1}{E_0} \int_{0}^{\infty} \frac{\exp\left(-\frac{y}{B_1}\right)}{(1+D_1 y)(1+D_0 y)} dy$$
(56)

where $\frac{1}{B_1} = \frac{\xi}{B_0} + \frac{1}{E_0}$. Further, K_1 and K_2 can be obtained as follows:

• If $D_1 = D_0$, K_1 and K_2 are calculated with the help of [22, Eq.(3.353.2)] and [22, Eq.(3.353.3)], respectively, as

$$K_{1} = D_{0}A_{1} \int_{0}^{\infty} \frac{\exp\left(-\frac{y}{B_{1}}\right)}{(1+D_{0}y)^{3}} dy = A_{1} \left\{ \frac{1}{2} - \frac{1}{2D_{0}B_{1}} + \frac{\exp\left(\frac{1}{D_{0}B_{1}}\right)}{2D_{0}^{2}B_{1}^{2}} \Gamma\left[0, \frac{1}{D_{0}B_{1}}\right] \right\}$$
(57)

$$K_2 = \frac{A_1}{E_0} \int_0^\infty \frac{\exp\left(-\frac{y}{B_1}\right)}{(1+D_1y)^2} dy = \frac{A_1}{D_0E_0} + \frac{A_1}{D_0^2E_0B_1} \exp\left(\frac{1}{D_0B_1}\right) E_i\left(-\frac{1}{D_0B_1}\right)$$
(58)

• If $D_1 \neq D_0$, we can obtain K_1 and K_2 , respectively, as follows:

$$K_1 = D_0 A_1 \int_0^\infty \frac{\exp\left(-\frac{y}{B_1}\right)}{(1+D_0 y)^2 (1+D_1 y)} dy = K_{11} - K_{12} + K_{13}$$
(59)

$$K_2 = \frac{A_1}{E_0} \int_0^\infty \frac{\exp\left(-\frac{1}{B_1}\right)}{(1+D_1y)(1+D_0y)} dy = K_{21} - K_{22}$$
(60)

where K_{11} , K_{12} , K_{13} , K_{21} , and K_{22} are calculated as follows:

$$K_{11} = \frac{A_1 D_0^2}{(D_0 - D_1)} \int_0^\infty \frac{\exp\left(-\frac{y}{B_1}\right)}{(1 + D_0 y)^2} dy$$

= $\frac{D_0 A_1}{D_0 - D_1} + \frac{A_1}{B_1 (D_0 - D_1)} \exp\left(\frac{1}{D_0 B_1}\right) E_i \left[-\frac{1}{D_0 B_1}\right]$ (61)

$$K_{12} = \frac{A_1 D_0^2 D_1}{(D_0 - D_1)^2} \int_0^\infty \frac{\exp\left(-\frac{y}{B_1}\right)}{1 + D_0 y} dy = \frac{A_1 D_0 D_1}{(D_0 - D_1)^2} \exp\left(\frac{1}{D_0 B_1}\right) \Gamma\left[0, \frac{1}{D_0 B_1}\right]$$
(62)

$$K_{13} = \frac{A_1 D_0 D_1^2}{(D_0 - D_1)^2} \int_0^\infty \frac{\exp\left(-\frac{y}{B_1}\right)}{1 + D_1 y} dy = \frac{A_1 D_0 D_1}{(D_0 - D_1)^2} \exp\left(\frac{1}{B_1 D_1}\right) \Gamma\left[-\frac{1}{B_1 D_1}\right]$$
(63)

$$K_{21} = \frac{D_0 A_1}{E_0 (D_0 - D_1)} \int_0^\infty \frac{\exp\left(-\frac{y}{B_1}\right)}{1 + D_0 y} dy = \frac{A_1}{E_0 (D_0 - D_1)} \exp\left(\frac{1}{D_0 B_1}\right) \Gamma\left[0, \frac{1}{D_0 B_1}\right]$$
(64)

$$K_{22} = \frac{A_1 D_1}{E_0 (D_0 - D_1)} \int_0^\infty \frac{\exp\left(-\frac{y}{B_1}\right)}{1 + D_1 y} dy = \frac{A_1}{E_0 (D_0 - D_1)} \exp\left(\frac{1}{B_1 D_1}\right) \Gamma\left[0, \frac{1}{B_1 D_1}\right]$$
(65)

It is noted that K_{11} is solved using [22, Eq.(3.353.3)] while K_{12} , K_{13} , K_{21} , K_{22} are reached with the help of [22, Eq.(3.352.4)].

Then, the final expression of $P_{\text{out,sec}}$ is obtained as

• For $D_1 = D_0$,

$$P_{\text{out,sec}} = 1 - \frac{A_1}{2} + \frac{A_2}{2D_0B_1} - \frac{A_1}{2D_0^2B_1^2} \exp\left(\frac{1}{D_0B_1}\right)\Gamma\left[0, \frac{1}{D_0B_1}\right] - \frac{A_1}{D_0E_0} - \frac{A_1}{D_0^2E_0B_1} \exp\left(\frac{1}{D_0B_1}\right)\text{Ei}\left(-\frac{1}{D_0B_1}\right)$$
(66)

• For $D_1 \neq D_0$,

$$P_{\text{out,sec}} = 1 - \frac{D_0 A_1}{D_0 - D_1} - \frac{A_1}{B_1 (D_0 - D_1)} \exp\left(\frac{1}{D_0 B_1}\right) E_i \left[-\frac{1}{D_0 B_1}\right] \\ + \frac{A_1 D_0 D_1}{(D_0 - D_1)^2} \left\{ \exp\left(\frac{1}{D_0 B_1}\right) \Gamma\left[0, \frac{1}{D_0 B_1}\right] - \exp\left(\frac{1}{B_1 D_1}\right) \Gamma\left[-\frac{1}{B_1 D_1}\right] \right\} \\ + \frac{A_1}{E_0 (D_0 - D_1)} \left\{ \exp\left(\frac{1}{B_1 D_1}\right) \Gamma\left[0, \frac{1}{B_1 D_1}\right] - \exp\left(\frac{1}{D_0 B_1}\right) \Gamma\left[0, \frac{1}{D_0 B_1}\right] \right\}$$
(67)

V. NUMERICAL RESULTS

In this section, the numerical results are presented to analyze the impact of primary network parameters, SU maximum transmit power limit and channel mean powers among users on the system performance. Further, we also study the effect of the presence of the SU on the primary network security. Unless otherwise stated, the following system parameter is used for both simulation and analysis: system bandwidth B = 5 MHz, e.g., bandwidth of UMTS or LTE channel.

A. SU SEP

Fig. 2 illustrates the SU SEP for BPSK modulation with different values of the SU maximum transmit SNR γ_{max} , $\gamma_{\text{max}} = P_{\text{pk}}/N_0$, and primary network setting parameters.

- Case 1: It is observed that the SU SEP decreases with respect to the increase of the PU transmit SNR, P_p/N₀. This is due to the fact that when P_p/N₀ increases, the SU-Tx transmit SNR also increases following (23). However, as P_p/N₀ increases further, e.g. P_p/N₀ > 8 dB, the SU-Tx transmit SNR can not increase further as it is bounded by γ_{max}. As a result, the PU transmit SNR become a strong interference source to the SU which leads to the increase of the SU SEP.
- Case 2: We set $\gamma_{\text{max}} = 10 \text{ dB}$, and then compare the change of the SEP to the Case 1 where $\gamma_{\text{max}} = 15 \text{ dB}$. It is easy to see that the SEP is obtained optimal value at $P_p/N_0 = 2 \text{ dB}$ and then increase rapidly as PU transmit SNR increases further, $P_p/N_0 > 2$. Clearly, the higher γ_{max} is, the degradation of the SEP is slower.

To observe the impact of the PU target rate r_p and outage threshold θ_{th} on the SEP, we consider two following cases:

- Case 3: By increasing $r_p = 32$ Kbps (Case 1) to $r_p = 42$ Kbps, the SU SEP increases, i.e, the system performance decreases. This can be explained by the fact that increase of r_p leads to higher SINR at the PU-Rx. Accordingly, the SU transmit SNR must decrease to satisfy the PU outage constraint, and this results in the degradation of the SU SEP.
- Case 4: We compare the SU SEP with PU outage constraint $\theta_{th} = 0.03$ to Case 1 with $\theta_{th} = 0.01$. Clearly, the SU SEP is decreased due to the relaxing of the PU outage constraint.

In Fig. 3, the impact of the channel mean powers of the interference links between primary and secondary networks and PU-Tx \rightarrow PU-Rx link on the SU SEP are illustrated.

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- Cases 5, 6 and 7: It can be observed that the SU SEP becomes high when the channel mean powers of both SU-Tx→PU-Rx and PU-Tx→SU-Rx interference links increase. In particular, when the channel power of the SU-Tx→PU-Rx link increases Ω_α = 0.5 in Case 5 to Ω_α = 2 in Case 7, the SU SEP is high. This is due to the fact that when Ω_α is high, the PU-Rx suffers strong interference from the SU-Tx. Accordingly, the SU-Tx must reduce its transmit power to guarantee the PU outage constraint. It is also seen that by increasing the channel mean power of the PU-Tx→SU-Rx from Ω_β = 0.5 (Case 6) to Ω_β = 2 (Case 7), the SU SEP becomes high. In this case, the PU-Tx becomes a interference source to the SU-Rx which results in the degradation of the secondary network performance.
- Case 8: We can also observe that the channel mean power of the PU-Tx→PU-Rx plays an important role on the secondary network performance. For instance, by increasing Ω_h = 4 (Case 7) to Ω_h = 6 (Case 8), the SU SEP decreases significantly. This can be explained by the fact that when Ω_h increases, the PU outage probability decreases resulting in the increase of the the SU transmit SNR.

In addition, the SU SEP decreases as Ω_{β} decreases as shown in Fig. 4 for different modulation schemes. Therefore, as expected, the secondary network performance is degraded as the channel mean powers of the interference links between primary and secondary networks become high. It can be noted that the above results in Figs. 2, 3 and 4 are in accordance with the SU transmit power policy given in (23).

B. Probability of Existence of Non-zero Secrecy Capacity of the PU

Fig. 5 and Fig. 6 illustrate the probability of existence of secrecy capacity of the PU. We can see that this probability does not change with the increase of the PU-Tx transmit SNR for the case of identical channel mean powers and for different values of the SU maximum transmit SNR. In fact, the probability of existence of secrecy capacity strongly depends on the channel condition of the SU-Tx \rightarrow EAV link. It can be observed that the primary network security is enhanced when the channel mean power of the interference link SU-Tx \rightarrow EAV Ω_{φ} increases. For example, the probability of existence of secrecy capacity increases significantly in Fig. 5 by increasing $\Omega_{\varphi} = 4$ to $\Omega_{\varphi} = 7,10$ and from $\Omega_{\varphi} = 4$ to $\Omega_{\varphi} = 8$ in Fig. 6, respectively. Here, the SU-Tx becomes a strong interference source to the EAV which degrades the received SINR at the EAV, and hence the primary network security becomes high. Moreover, we can see from the Fig. 6 that when Ω_{α} decreases, the primary network security is also improved. This is can be explained by the fact that decreasing Ω_{α} results in the increase of the SU-Tx transmit SNR which results in high interference to the EAV. Thus, curves in Fig. 5 and Fig. 6 show that the presence of the SU contributes significantly to the primary network security.

C. Outage Probability of Secrecy Capacity of the PU

Fig. 7 and Fig. 8 illustrate the outage probability of secrecy capacity of the PU.

- Cases 9 and 10: As discussed for the probability of existence of secrecy capacity in Fig. 5, it can also be observed in Fig. 7 that the outage probability of secrecy capacity does not change with the increase of the PU-Tx transmit SNR for the case of identical channels.
- Cases 11 and 12: When the channel mean power of the SU-Tx→EAV link increases, e.g.,
 Ω_φ = 8 in both cases, the primary network security is improved compared to Cases 9 (Ω_φ = 2) and 10 (Ω_φ = 4), respectively.

Furthermore, Fig. 8 shows that the outage probability of secrecy capacity decreases as the channel mean power of the SU-Tx \rightarrow PU-Rx link decreases, $\Omega_{\alpha} = 2$ to 0.5. Again, the SU-Tx transmit SNR increases due to the decrease of Ω_{α} and hence the interference from the SU-Tx to EAV becomes high. Therefore, results illustrated in Fig. 5, Fig. 6, Fig. 7, and Fig. 8 reveal that the primary network security strongly depends on the channel condition of the SU-Tx \rightarrow EAV and SU-Tx transmit power policy. In addition, the outage probability of secrecy capacity decreases as the channel mean power of the PU-Tx \rightarrow PU-Rx link increases, e.g., $\Omega_h = 4$ to 8 with $\Omega_{\varphi} = 4$ as shown in Fig. 8. This is expected since the PU-Tx \rightarrow PU-Rx link becomes better than the PU-Tx \rightarrow EAV link in this scenario.

VI. CONCLUSIONS

In this paper, we have studied the performance of a CRN under the joint constraint of the PU outage and maximum transmit power limit of the SU. The considered model is also a typical D2D communication model where the PU-Tx \rightarrow PU-Rx link is an instance of uplink or downlink of cellular network while the SU-Tx \rightarrow SU-Rx link is the instance of D2D communication link. Accordingly, the adaptive transmit power for the SU-Tx and analytical expression for the SU SEP has been derived. Further, analytical expressions of the outage probability of secrecy capacity and probability of existence of non-zero secrecy capacity of the PU have been obtained. In addition,

the impact of the channel conditions among users, SU peak transmit power on the system performance is investigated. Most importantly, our results indicate that the primary network security strongly depends on the channel conditions of the SU-Tx \rightarrow EAV link and SU transmit power policy. Also, it reveals that the presence of the SU contributes to the primary network security enhancement. The obtained results may provide valuable information to operators and system designers in a spectrum sharing CRN where the PU and SU can cooperate to combat the security attack.

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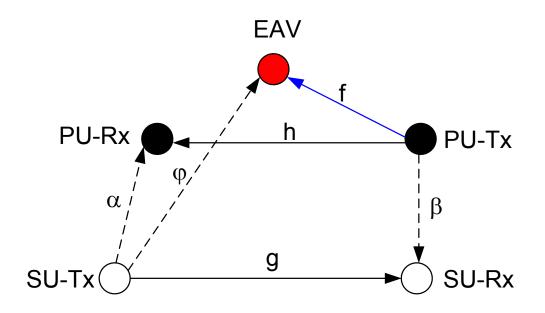


Fig. 1. A system model of cognitive radio network in which SU and PU share the same spectrum while an EAV illegally listens to the PU communication (dashed lines: Interference links; solid lines: Data information links).

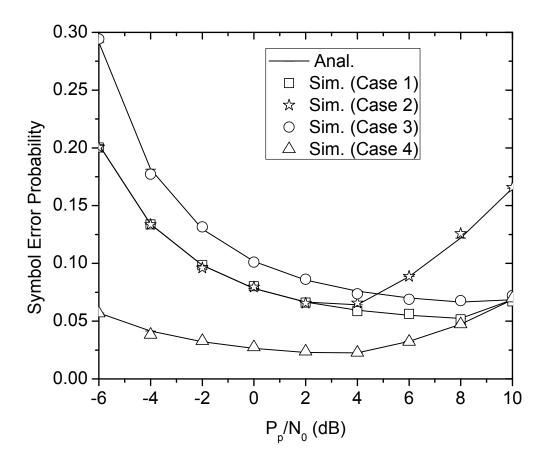


Fig. 2. SU SEP versus PU transmit SNR with BPSK modulation scheme, $\Omega_g = \Omega_h = 4$ and $\Omega_\alpha = \Omega_\beta = 2$. Case 1: $\gamma_{\text{max}} = 15$ dB, $r_p = 32$ Kbps, $\theta_{th} = 0.01$; Case 2: $\gamma_{\text{max}} = 10$ dB, $r_p = 32$ Kbps, $\theta_{th} = 0.01$; Case 3: $\gamma_{\text{max}} = 15$ dB, $r_p = 42$ Kbps, $\theta_{th} = 0.01$; Case 4: $\gamma_{\text{max}} = 15$ dB, $r_p = 32$ Kbps, $\theta_{th} = 0.03$.

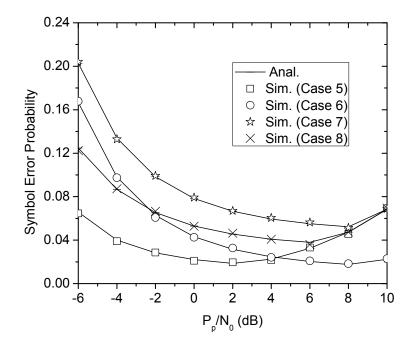


Fig. 3. SU SEP versus PU transmit SNR with BPSK modulation scheme, $\gamma_{max} = 15$ dB, $r_p = 32$ Kbps, $\theta_{th} = 0.01$ and $\Omega_g = 4$. Case 5: $\Omega_h = 4$, $\Omega_\alpha = 0.5$, $\Omega_\beta = 2$; Case 6: $\Omega_h = 4$, $\Omega_\alpha = 2$, $\Omega_\beta = 0.5$; Case 7: $\Omega_h = 4$, $\Omega_\alpha = \Omega_\beta = 2$; Case 8: $\Omega_h = 6$, $\Omega_\alpha = 2$, $\Omega_\beta = 2$.

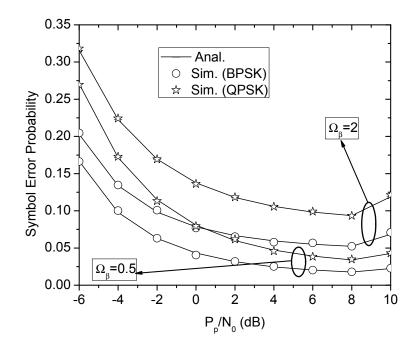


Fig. 4. SU SEP versus PU transmit SNR with $\gamma_{max} = 15$ dB, $r_p = 32$ Kbps, $\theta_{th} = 0.01$, $\Omega_g = \Omega_h = 4$ and $\Omega_{\alpha} = 2$.

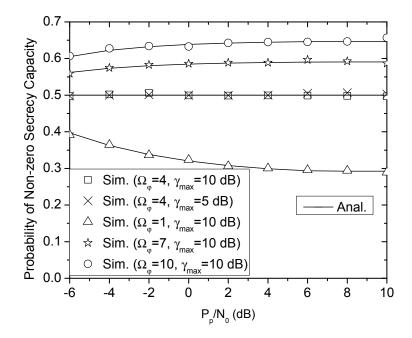


Fig. 5. Probability of existence of a non-zero secrecy capacity of the PU versus PU transmit SNR with $r_p = 32$ Kbps, $\theta_{th} = 0.01$ and $\Omega_f = \Omega_g = \Omega_h = \Omega_\alpha = \Omega_\beta = 4$.

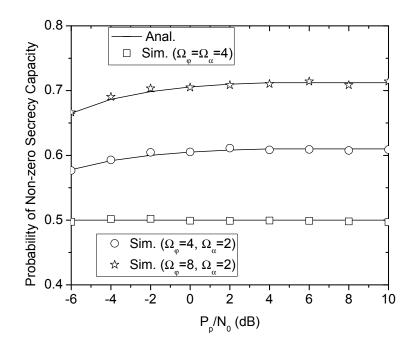


Fig. 6. Probability of existence of non-zero secrecy capacity of the PU versus PU transmit SNR with $\gamma_{\text{max}} = 15$ dB, $r_p = 32$ Kbps, $\theta_{th} = 0.01$ and $\Omega_f = \Omega_g = \Omega_h = \Omega_\beta = 4$.

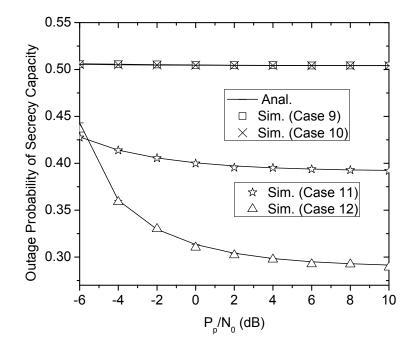


Fig. 7. Outage probability of secrecy capacity of the PU versus PU transmit SNR with $R_s = r_p = 32$ Kbps, $\theta_{th} = 0.01$ and $\gamma_{max} = 15$ dB. Case 9: $\Omega_f = \Omega_h = \Omega_\alpha = \Omega_\varphi = 2$; Case 10: $\Omega_f = \Omega_h = \Omega_\alpha = \Omega_\varphi = 4$; Case 11: $\Omega_f = \Omega_h = \Omega_\alpha = 4$, $\Omega_\varphi = 8$; Case 12: $\Omega_f = \Omega_h = \Omega_\alpha = 2$, $\Omega_\varphi = 8$.

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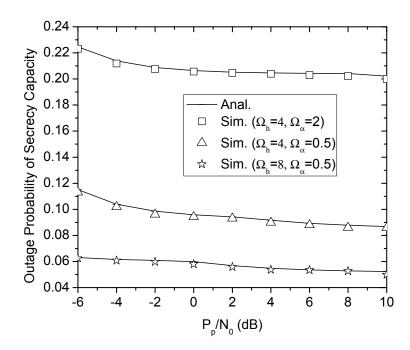


Fig. 8. Outage probability of secrecy capacity of the PU versus PU transmit SNR with $R_s = r_p = 32$ Kbps, $\theta_{th} = 0.01$, $\gamma_{max} = 15$ dB and $\Omega_f = \Omega_{\varphi} = 4$.