

# Secrecy Analysis of DCSK-Based PLC Systems with Multiple Eavesdroppers

In this chapter <sup>2</sup>, we study the PLS performance of low-frequency PLC systems against multiple eavesdroppers by employing DCSK based modulation technique. A wiretap power line channel model is investigated by considering two different cases a) when all the channels are assumed to be IID following Log-normal distribution and b) when the wiretap channels are considered to be identical but correlated Log-normally distributed and independent of the main channel. Contemporaneously, the Bernoulli-Gaussian random process models the PLC noise. Further, a comprehensive PLS study of the considered PLC system is characterized in terms of the ASC, SOP, and SPSC. We also propose an algorithm to maximize the secrecy throughput under security and reliability constraints. Moreover, to obtain essential insights, we reveal the impact of various crucial parameters onto the proposed system.

## 3.1 Introduction

Grid refers to an intelligent, next-generation power grid system based on modern ICTs that are used to supply, manage, configure, coordinate, and control the electricity network from the power plant to the home via two-way digital communication. The Smart Grid is envisioned as a cyber-physical system supported by hybrid ICTs such as wireless and wireline, which utilize Wi-Fi, coaxial cables, fiber optics, wireless sensor networks, power-line networks, and hybrid PLC/wireless communication [Amarsingh *et al.*, 2014; Galli *et al.*, 2011b; d. M. B. A. Dib *et al.*, 2018]. However, individual deployment of any ICT is not preferable in all scenarios of Smart Grid communications. Among these ICTs, PLC is recognized as an attractive choice for many smart grid applications from indoor (in the home) to outdoor (to the home) scenarios, including advanced metering infrastructure and home automation. PLC exploits the electricity network to deliver the digital data. Moreover, PLC networks offer several advantages over other technologies, such as providing high-speed Internet access, substantial geographical coverage, and low installation and maintenance costs.

In recent years, the world's power grids have been continuously attacked by cybercriminals, which has been a cause of power outages in certain regions. For instance, recently, in March 2020, there was a massive power outage in Mumbai, India [INDIA TODAY, 2022]. These outages raise the concern of national security as well as data security of the individuals. The modernization of the power grid and the use of various smart applications are widening the potential of eavesdroppers and making them more vulnerable to intrusion. Therefore, offering unbreachable data security is always a significant issue in the Smart Grid communications network. Traditionally, in data communication, key-based cryptography encryption techniques were used to provide secure

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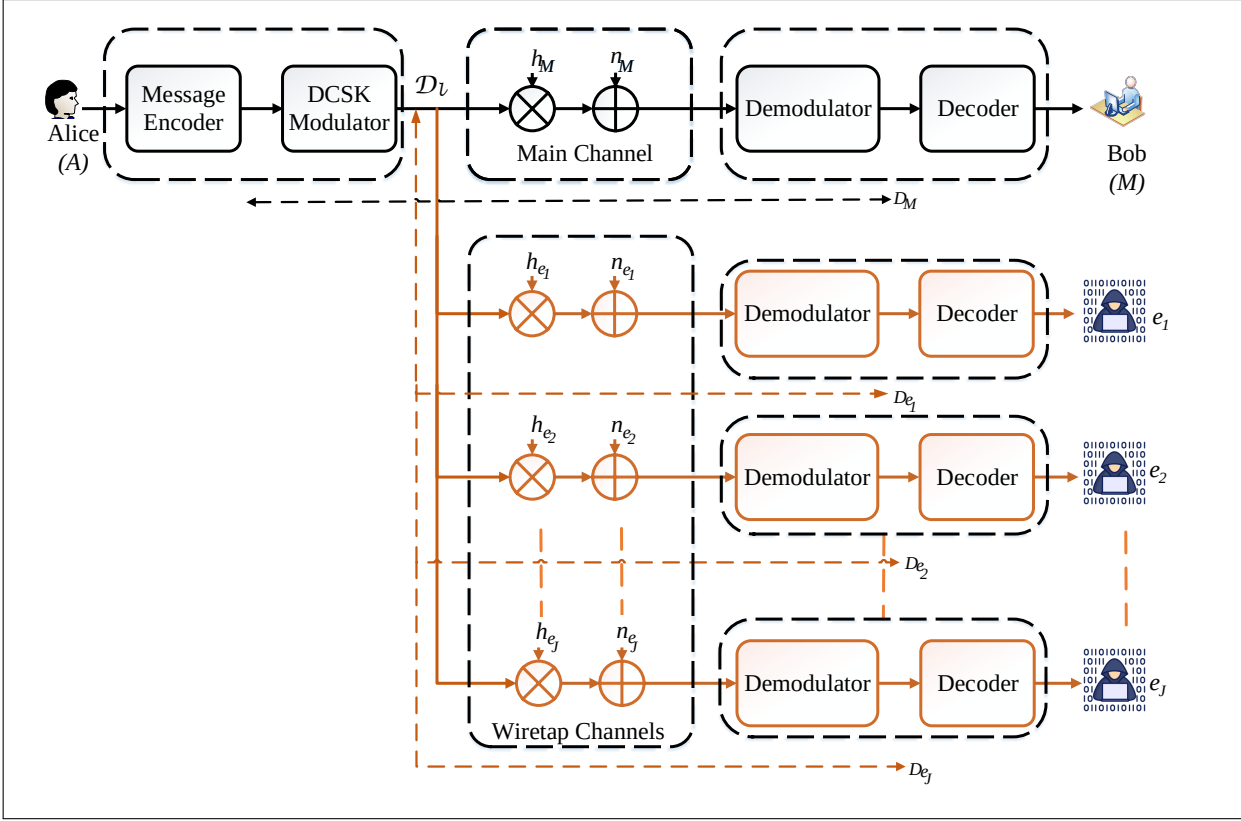


**Figure 3.1:** Basic PLC system model in the presence of multiple eavesdroppers.

communication against an eavesdropper [Kartalopoulos, 2006b]. Nevertheless, these encryption techniques are loaded with high computation complexity and become less safe due to computer technology advancement.

Recently, PLS has been extensively studied in wireless and wired communication systems and proclaimed an alternative approach to safeguard the data instead of entirely relying on traditional cryptographic algorithms. In [Pittolo and Tonello, 2013] and [Pittolo and Tonello, 2014], the PLS performance of a SISO PLC system and a wireless system were analyzed and compared in the presence of a single eavesdropper. The authors demonstrated that the PLC systems have a lower secrecy rate than wireless communication systems. In [Zhuang and Lampe, 2014], the secrecy performance of a MIMO PLC system was evaluated against a single eavesdropper, where it is revealed that MIMO PLC has higher secrecy than SISO PLC systems. The authors in [Salem *et al.*, 2017] investigated the PLS performance of cooperative PLC systems over correlated Log-normally distributed channels in the presence of a passive eavesdropper. Similarly, in [Mohan *et al.*, 2019], the closed-form expression of average ASC, SOP, and SPSC were derived for independent and correlated PLC channels. The superiorities of the DCSK modulation scheme have attracted significant attention of the research community motivating them to analyze its performance with both wireless and wireline communication technologies. In recent years, several studies have been done introducing the DCSK modulation scheme in PLC. In [Kaddoum and Tadayon, 2017], the BER performance of the DCSK-based PLC system was investigated, where a multipath PLC channel was considered in the presence of background, impulsive, and phase noise. Moreover, it was shown that DCSK outperformed DS-DPSK and the DS-CDMA with imperfect CSI. Similarly, the authors of [Zheng *et al.*, 2017] studied the BER performance of M-DCSK with background, impulsive, and phase noises over narrowband PLC. Besides that, they concluded that M-DCSK performs better than DS-MDPSK. Further, a replica piecewise M-ary DCSK scheme was proposed [Miao *et al.*, 2020] for

PLC in the presence of asynchronous impulsive noise. The authors presented that RP-MDCSK has a significantly lower BER than DCSK and DS-MDPSK.

The remainder of this chapter is organized as follows: Section 3.2 presents the considered PLC system model, where the DCSK system, received power, PLC channel and noise models, and the characterization of the instantaneous SNR are contemplated. The PLS study of the proposed PLC system conducted in terms of ASC, SOP, and SPSC under different cases is presented in Section 3.3. Further, the asymptotic analysis of SOP is conducted. In Section 3.4, we demonstrate and discuss the numerical results. Section 3.5 concludes with the chapter summary.

## 3.2 System Description

Let us consider a discrete memoryless Wyner's wiretap PLC channel model presented in Fig. 3.1, where Alice ( $A$ ) secretly transmits the information to an authorized user, Bob ( $M$ ), via the main channel. At the same time, multiple eavesdroppers ( $E$ ) want to tap the transmitted information passively over the wiretap channels. The set of  $J$  eavesdroppers are denoted as  $E = \{e_j | j = 1, 2, \dots, J\}$ .

### 3.2.1 Received Power

The received signals at  $M$  and  $e_j$  are given by

$$r_k = \sqrt{P_{R_k}} h_k \mathcal{D}_l + n_k, k \in \{M, e_j\}. \quad (3.1)$$

In (3.1),  $h_M$  and  $h_{e_j}$  are the complex channel gains of the main channel and the  $j^{\text{th}}$  eavesdropper channels, respectively. The considered PLC system consists of fewer branches with short lengths (0-500 m) and matched load. Therefore, the coherence bandwidth of the PLC channel is greater than the transmitted signal bandwidth. Thus, the PLC channels undergo flat fading [Dubey *et al.*, 2014], [Mathur *et al.*, 2017]. In Eq. (3.1),  $n_M$  and  $n_{e_j}$  represent channel noise on the main channel and the eavesdropper channels, respectively, and  $\mathcal{D}_l$  denotes the single carrier DCSK modulated signal transmitted by  $A$ . The received power at  $M$  and  $e_j$  can be expressed as [Dubey *et al.*, 2014]

$$P_{R_k}(\text{dB}) = P_T(\text{dB}) - P_L(\text{dB/km}) \times D_k. \quad (3.2)$$

In (3.2),  $k \in \{M, e_j\}$ ,  $P_T$  indicates the transmitted power (in dB),  $P_L$  denotes the attenuation factor with distance in dB/km, and  $D_M$  and  $D_{e_j}$  are the distances between  $A$  to  $M$  and  $A$  to  $e_j$ , respectively. It should be noted that (3.2) represents the distance-dependent attenuation of the considered PLC channels [Dubey and Mallik, 2015], [Ferreira *et al.*, 2011, ch. 2]. The typical value of  $P_L$  lies in the range of 40-100 dB/km for PLC systems [Hooijen, 1998]. The analysis of the considered PLC system model has been carried out by assuming a low-voltage grid segment for the in-home communication scenario. Therefore, the effect of high voltage is neglected [Sendin *et al.*, 2014].

### 3.2.2 PLC Channel Model

In the proposed PLC system, we assume that the main channel and the eavesdropper channels are subjected to Log-normally distributed channel gain. The PDF of the PLC channel gain can be expressed as [Pan *et al.*, 2016]

$$f(h_k) = \frac{1}{h_k \sqrt{2\pi\sigma_k^2}} \exp\left(-\frac{(\ln h_k - \mu_k)^2}{2\sigma_k^2}\right). \quad (3.3)$$

In (3.3),  $k \in \{M, e_j\}$ ,  $\mu_k$  and  $\sigma_k^2$  denote mean and variance of the RV  $\ln h_k$ , and  $h_k \geq 0$ , respectively. The CSI of the main channel and the eavesdropper channels are presumed to be known.

### 3.2.3 Noise Modeling

In contrast to the conventional communication systems, the noise in the PLC systems is characterized by a mixture of background noise and impulsive noise [Ferreira *et al.*, 2011]. In the considered PLC system, the additive PLC channel noise is modeled by the Bernoulli-Gaussian random process [Ma *et al.*, 2005b]. Hence, the total noise can be characterized as

$$n_k = \mathcal{G}'_k + \mathcal{I}_k, \quad k \in \{M, e_j\}, \quad (3.4a)$$

$$\mathcal{I}_k = P_B \mathcal{G}''_k, \quad k \in \{M, e_j\}. \quad (3.4b)$$

In (3.4a) and (3.4b),  $\mathcal{G}'_k$  and  $\mathcal{G}''_k$  are Gaussian RVs representing background and impulsive noise component with zero mean and variances  $\sigma_{\mathcal{B}}^2$  and  $\sigma_{\mathcal{I}}^2$ , respectively.  $\mathcal{I}_k$  denotes the impulsive noise RV and  $P_B$  is the Bernoulli random process. Moreover, all the components in (3.4a) and (3.4b) are mutually independent.

Thus, the PDF of the PLC channel noise on the main channel ( $A$  to  $M$ ) and the eavesdropper channels ( $A$  to  $e_j$ ) is given by [Mathur *et al.*, 2018, Eq. (5)]

$$f(n_k) = \sum_{i=1}^2 p_i \mathcal{N}(0, \sigma_{k_i}^2), k \in \{M, e_j\}, i \in \{1, 2\}. \quad (3.5)$$

In (3.5),  $p_1 = 1 - p$ ,  $p_2 = p$ ,  $p$  is the arrival probability of the impulsive component of the Bernoulli-Gaussian noise,  $\sigma_{k_1}^2 = \sigma_{\mathcal{B}_k}^2$  is the background noise power, and  $\sigma_{k_2}^2 = \sigma_{\mathcal{B}_k}^2 (1 + K)$  is the noise power of both background and impulsive noises.  $K = \sigma_{\mathcal{I}_k}^2 / \sigma_{\mathcal{B}_k}^2$  denotes the the impulsive noise to the background noise power ratio and  $\sigma_{\mathcal{I}_k}^2$  is the impulsive noise power.

### 3.2.4 Characterization of the Instantaneous SNR

The instantaneous SNR of the received DCSK signal at  $M$  and  $e_j$  can be written as [Mathur *et al.*, 2018, Eq. (6)]

$$\gamma_k = \begin{cases} \gamma_{k_1} = \frac{|h_k|^2 P_{R_k}}{2\beta \sigma_{\mathcal{B}_k}^2} = \frac{|h_k|^2 \bar{\gamma}_k}{2\beta}, & \text{only background noise,} \\ \gamma_{k_2} = \frac{|h_k|^2 P_{R_k}}{2\beta \sigma_{\mathcal{B}_k}^2 (1 + K)} = \frac{|h_k|^2 \bar{\gamma}'_k}{2\beta}, & \text{with impulsive noise.} \end{cases} \quad (3.6)$$

In (3.6),  $k \in \{M, e_j\}$ ,  $\bar{\gamma}_k = P_{R_k} / \sigma_{\mathcal{B}_k}^2$  represents the average SNR when only background is present, and  $\bar{\gamma}'_k = \bar{\gamma}_k / (K + 1)$  denotes the average SNR when impulsive noise is also present. Further, based on the transformation of RV [Mathur *et al.*, 2018, Eqs. (8-9)], the PDF of the  $\gamma_{M_i}$  and  $\gamma_{e_{j_i}}$  can be written as

$$f_{\gamma_{k_i}}(\gamma_{k_i}) = \frac{1}{\gamma_{k_i} \sqrt{2\pi \sigma_{\gamma_{k_i}}^2}} \exp \left( -\frac{(\ln \gamma_{k_i} - \mu_{\gamma_{k_i}})^2}{2\sigma_{\gamma_{k_i}}^2} \right). \quad (3.7)$$

In (3.7),  $k \in \{M, e_j\}$ ,  $i \in \{1, 2\}$ ,  $\mu_{\gamma_{k_1}} = 2\mu_{h_k} + \ln \bar{\gamma}_k - \ln(2\beta)$ ,  $\mu_{\gamma_{k_2}} = 2\mu_{h_k} + \ln \bar{\gamma}'_k - \ln(2\beta)$ , and  $\sigma_{\gamma_{M_i}}^2 = \sigma_{\gamma_{e_{j_i}}}^2 = 4\sigma_{h_k}^2$ .

Thus, the CDF of  $\gamma_{M_i}$  and  $\gamma_{e_{j_i}}$  can be expressed as

$$\begin{aligned} F_{\gamma_{k_i}}(\gamma_{k_i}) &= \int_0^{\gamma_{k_i}} \frac{1}{\gamma_{k_i} \sqrt{2\pi \sigma_{\gamma_{k_i}}^2}} \exp \left( -\frac{(\ln \gamma_{k_i} - \mu_{\gamma_{k_i}})^2}{2\sigma_{\gamma_{k_i}}^2} \right) d\gamma_{k_i}, \\ &= \left[ 1 - \mathcal{Q} \left( \frac{\ln \gamma_{k_i} - \mu_{\gamma_{k_i}}}{\sigma_{\gamma_{k_i}}} \right) \right], k \in \{M, e_j\}. \end{aligned} \quad (3.8)$$

### 3.3 Physical Layer Security Analysis

In this section, we compute the PLS performance metrics in terms of ASC, SOP, and SPSC for the considered PLC system.

#### 3.3.1 Preliminaries

Generally, evaluating the closed-form expressions of the performance metrics involving Log-normal distribution is quite intractable [Pan *et al.*, 2016]. In this work, to aid the analysis of ASC, SOP, and SPSC, we utilize an accurate Gaussian approximation proposed by Holtzman which is described below [Holtzman, 1992].

If  $\Phi(x)$  is a real function of  $x$  that is following normal distribution with mean  $\mu$  and variance  $\sigma^2$ , that is,  $x \sim \mathcal{N}(\mu, \sigma^2)$ , then, the average value of  $\Phi(x)$  can be approximated upto three terms as follows:

$$\mathbb{E}[\Phi(x)] \approx \frac{2}{3}\Phi(\mu) + \frac{1}{6}\Phi(\mu + \sqrt{3}\sigma) + \frac{1}{6}\Phi(\mu - \sqrt{3}\sigma). \quad (3.9)$$

#### 3.3.2 Computation of ASC

Secrecy capacity is the maximum difference of mutual information of the main channel and eavesdropper channels [Pittolo and Tonello, 2014]. The instantaneous secrecy capacity  $\mathcal{C}_s$  for the proposed PLC system is defined as [Pan *et al.*, 2016]

$$\mathcal{C}_s = \max\{\ln(1 + \gamma_{M_i}) - \ln(1 + \gamma_{\max_i}), 0\}. \quad (3.10)$$

In (3.10),  $\gamma_{\max} = \max[\gamma_{e_1}, \dots, \gamma_{e_J}]^T$ .

1) *Case-I, When the main channel and all the eavesdropper channels are IID :*

Assume that the complex fading channel gain  $h_M$  and  $h_{e_1}, \dots, h_{e_J}$  of the main channel and the eavesdropper channels, respectively, are IID and subjected to Log-normal distribution. For this case, we consider an eavesdropper link with the maximum instantaneous SNR among all the eavesdropper's links, i.e,  $\gamma_{\max} = \max[\gamma_{e_1}, \dots, \gamma_{e_J}]^T$  and  $\ln \gamma_{\max} = \max[\ln \gamma_{e_1}, \dots, \ln \gamma_{e_J}]^T$ . Then, the CDF of  $\gamma_{\max}$  can be obtained using order statistics as [David and Nagaraja, 2004]

$$\begin{aligned} F_{\gamma_{\max_i}}(\gamma_i) &= \Pr \left[ \max_{1 \leq j \leq J} \{\gamma_{e_{j_i}}\} \leq \gamma_i \right] = \left[ F_{\gamma_{e_{j_i}}}(\gamma_i) \right]^J, \\ &= \left[ 1 - \mathcal{Q} \left( \frac{\ln \gamma_i - \mu_{\gamma_i}}{\sigma_{\gamma_i}} \right) \right]^J, i \in \{1, 2\}. \end{aligned} \quad (3.11)$$

Furthermore, according to order statistics [David and Nagaraja, 2004], the PDF of  $\gamma_{\max}$  can be computed as

$$\begin{aligned} f_{\gamma_{\max_i}}(\gamma_i) &= J \left[ F_{\gamma_{e_{j_i}}}(\gamma_i) \right]^{J-1} f_{\gamma_{e_{j_i}}}(\gamma_i), \\ &= J \left[ 1 - \mathcal{Q} \left( \frac{\ln \gamma_i - \mu_{\gamma_i}}{\sigma_{\gamma_i}} \right) \right]^{J-1} f_{\gamma_{e_{j_i}}}(\gamma_i). \end{aligned} \quad (3.12)$$

The ASC for the considered PLC system can be expressed as [Pan *et al.*, 2016]

$$\bar{\mathcal{C}}_s(\gamma_M, \gamma_{\max}) = \sum_{i=1}^2 p_i \mathbb{E} \left[ \mathcal{C}_{s_i}(\gamma_{M_i}, \gamma_{\max_i}) \right]. \quad (3.13)$$

In (3.13),

$$\begin{aligned}
\mathbb{E}[\mathcal{C}_{s_i}(\gamma_{M_i}, \gamma_{\max_i})] &= \int_0^\infty \int_0^\infty \mathcal{C}_{s_i}(\gamma_{M_i}, \gamma_{\max_i}) f_{\gamma_{M_i}}(\gamma_{M_i}) f_{\gamma_{\max_i}}(\gamma_{\max_i}) d\gamma_{\max_i} d\gamma_{M_i} \\
&= \int_0^\infty \ln(1 + \gamma_{M_i}) f_{\gamma_{M_i}}(\gamma_{M_i}) F_{\gamma_{\max_i}}(\gamma_{M_i}) d\gamma_{M_i} \\
&\quad - \int_0^\infty \ln(1 + \gamma_{\max_i}) f_{\gamma_{\max_i}}(\gamma_{\max_i}) [1 - F_{\gamma_{M_i}}(\gamma_{\max_i})] d\gamma_{\max_i} \\
&= \mathcal{C}_{M_i}(\gamma_{M_i}) - \mathcal{C}_{\max_i}(\gamma_{\max_i}).
\end{aligned} \tag{3.14}$$

In (3.14),

$$\mathcal{C}_{M_i}(\gamma_{M_i}) = \int_0^\infty \ln(1 + \gamma_{M_i}) \left[ 1 - \mathcal{Q}\left(\frac{\ln \gamma_{M_i} - \mu_{\gamma_{\max_i}}}{\sigma_{\gamma_{\max_i}}}\right) \right]^J f(\gamma_{M_i}) d\gamma_{M_i}, \tag{3.15}$$

$$\mathcal{C}_{\max_i}(\gamma_{\max_i}) = \int_0^\infty \ln(1 + \gamma_{\max_i}) \left[ \mathcal{Q}\left(\frac{\ln \gamma_{\max_i} - \mu_{\gamma_{M_i}}}{\sigma_{\gamma_{M_i}}}\right) \right]^J f(\gamma_{\max_i}) d\gamma_{\max_i}. \tag{3.16}$$

Utilizing (3.9) into (3.15) and (3.16), the closed-form expressions for (3.15) and (3.16) can be obtained, respectively, as

$$\mathcal{C}_{k_i}(\gamma_{k_i}) \approx \frac{2}{3} \Psi_{k_i}(\mu_{\gamma_{k_i}}) + \frac{1}{6} \Psi_{k_i}(\mu_{\gamma_{k_i}} + \sqrt{3} \sigma_{\gamma_{k_i}}) + \frac{1}{6} \Psi_{k_i}(\mu_{\gamma_{k_i}} - \sqrt{3} \sigma_{\gamma_{k_i}}). \tag{3.17}$$

In (3.17),  $k \in \{M, \max\}$ ,  $\Psi_{M_i}(x) = \ln(1 + \exp(x)) [1 - \mathcal{Q}((x - \mu_{\gamma_{\max_i}})/\sigma_{\gamma_{\max_i}})]^J$ , and  $\Psi_{\max_i}(x) = \ln(1 + \exp(x)) [\mathcal{Q}((x - \mu_{\gamma_{M_i}})/\sigma_{\gamma_{M_i}})]^J$ .

Finally, substituting (3.17) into (3.13), we can obtain the closed-form expression for the ASC.

2) *Case-II, When all the eavesdropper channels are correlated but independent of the main channel:*

In this case, the complex fading channel gain  $h_{e_1}, \dots, h_{e_J}$  of the multiple eavesdropper channels are assumed to be identical but correlated Log-normally distributed. Under perfect secrecy condition, we assume that the multiple eavesdroppers receive differently faded signals. Therefore, we choose only one eavesdropper with maximum instantaneous SNR such as  $\gamma_{\max} = \max[\gamma_{e_1}, \dots, \gamma_{e_J}]^T$  and  $\ln \gamma_{\max} = \max[\ln \gamma_{e_1}, \dots, \ln \gamma_{e_J}]^T$ .

Let  $\gamma_{e_{j_i}} = [\gamma_{e_{1_i}}, \dots, \gamma_{e_{J_i}}]^T$  and  $\ln \gamma_{e_{j_i}} = [\ln \gamma_{e_{1_i}}, \dots, \ln \gamma_{e_{J_i}}]^T$ . The joint PDF of the SNR of the multiple correlated eavesdroppers can be written as [Dubey *et al.*, 2014]

$$f_{\gamma_{E_i}}^{\text{corr}}(\gamma_{e_{1_i}}, \dots, \gamma_{e_{J_i}}) = \frac{\exp\left[-\frac{1}{2}(\ln \gamma_{E_i} - \mu_{\gamma_{E_i}})^T \Lambda_{\gamma_{E_i}}^{-1} (\ln \gamma_{E_i} - \mu_{\gamma_{E_i}})\right]}{(2\pi)^{J/2} |\Lambda_{\gamma_{E_i}}|^{1/2} \prod_{j=1}^J \gamma_{E_i}}. \tag{3.18}$$

In (3.18),  $i \in \{1, 2\}$ ,  $E_i = \{e_{j_i} | j = 1, 2, \dots, J\}$ ,  $\mu_{\gamma_{E_i}} = \mu_{\gamma_{E_i}} \mathbf{1}_J$ , and  $\Lambda_{\gamma_{E_i}}$  is given as

$$\Lambda_{\gamma_{E_i}} = \sigma_{\gamma_{E_i}}^2 \begin{bmatrix} 1 & \rho_h & \dots & \rho_h^{J-1} \\ \rho_h & 1 & \dots & \rho_h^{J-2} \\ \vdots & \vdots & \ddots & \vdots \\ \rho_h^{J-1} & \rho_h^{J-2} & \dots & 1 \end{bmatrix}. \tag{3.19}$$

In (3.19),  $\mathbf{1}_J$  denotes  $J \times 1$  vector of ones and  $\rho_h^{|x-y|} = \mathbb{E}[\{(\ln h_x - \mu_x)(\ln h_y - \mu_y)\}/\sigma_h^2]$  represents the correlation coefficient between any two channels  $x$  and  $y$ . Accordingly, by integrating (3.18), the joint CDF of the SNR of the multiple correlated eavesdroppers can be obtained as

$$F_{\gamma_{\max_i}}^{\text{corr}}(\gamma_i) = \Pr \left[ \max_{1 \leq j \leq J} \{\gamma_{e_{j_i}}\} \leq \gamma_i \right] \\ = \int_0^{\gamma_i} \dots \int_0^{\gamma_i} \frac{\left[ \frac{1}{2} (\ln \gamma_{\mathbf{E}_i} - \boldsymbol{\mu}_{\gamma_{\mathbf{E}_i}})^T \boldsymbol{\Lambda}_{\gamma_{\mathbf{E}_i}}^{-1} (\ln \gamma_{\mathbf{E}_i} - \boldsymbol{\mu}_{\gamma_{\mathbf{E}_i}}) \right]}{(2\pi)^{J/2} |\boldsymbol{\Lambda}_{\gamma_{\mathbf{E}_i}}|^{1/2} \prod_{j=1}^J \gamma_{\mathbf{E}_i}} d\gamma_{e_{1_i}} \dots d\gamma_{e_{J_i}}. \quad (3.20)$$

By applying the transformation  $\mathbf{g} = \ln \gamma_{e_{j_i}}$  for  $j = 1, \dots, J$ .

$$F_{\gamma_{\max_i}}^{\text{corr}}(\gamma_i) = \int_0^{\ln \gamma_i} \dots \int_0^{\ln \gamma_i} \frac{\left[ \frac{1}{2} (\ln \mathbf{g} - \boldsymbol{\mu}_{\mathbf{g}})^T \boldsymbol{\Lambda}_{\mathbf{g}}^{-1} (\ln \mathbf{g} - \boldsymbol{\mu}_{\mathbf{g}}) \right]}{(2\pi)^{J/2} |\boldsymbol{\Lambda}_{\mathbf{g}}|^{1/2}} d\mathbf{g}_1 \dots d\mathbf{g}_J. \quad (3.21)$$

In (3.21),  $\mathbf{g} = [\mathbf{g}_1, \dots, \mathbf{g}_J]^T$  represents a Gaussian random vector with mean vector  $\boldsymbol{\mu}_{\mathbf{g}}$ , covariance matrix  $\boldsymbol{\Lambda}_{\mathbf{g}}$ , and distributed as  $\mathcal{N}(\boldsymbol{\mu}_{\mathbf{g}}, \boldsymbol{\Lambda}_{\mathbf{g}})$ . Generally, it is hard to compute the  $J$ -fold integral in (3.21). Therefore, using a constant correlation model, the  $J$ -fold integral can be deduced to a single integral by a specific transformation given in [Dubey *et al.*, 2014], [Gupta, 1963]. Further, Eq. (3.21) can be approximated to a constant correlation matrix by applying the transformation given in [Karagiannidis *et al.*, 2003, Section IV] as follows:

$$\boldsymbol{\Lambda}_{\gamma_{\mathbf{E}_i}} = \sigma_{\gamma_i}^2 \begin{bmatrix} 1 & \rho & \dots & \rho \\ \rho & 1 & \dots & \rho \\ \cdot & \cdot & \dots & \cdot \\ \rho & \cdot & \dots & 1 \end{bmatrix}, \sum_{j=1}^{J-1} (\rho_h^j - \rho) = 0. \quad (3.22)$$

In (3.22),  $\rho = (\rho_h(1 - \rho_h^{J-1})) / ((J-1)(1 - \rho_h))$ . Hence, utilizing [Gupta, 1963],  $\mathbf{g}_1, \dots, \mathbf{g}_J$  can be obtained from  $J+1$  independent standard Gaussian distributed variables  $u_1, \dots, u_J, v$  as

$$\mathbf{g}_j = \sigma_{\gamma_i} (\sqrt{(1-\rho)}u_j + \sqrt{\rho}v) + \mu_{\gamma_i}, j = 1, \dots, J. \quad (3.23)$$

Substituting (3.23) in (3.21), we get

$$F_{\gamma_{\max_i}}^{\text{corr}}(\gamma_i) = \int_{-\infty}^{\infty} \left[ 1 - \mathcal{Q} \left( \frac{\ln \gamma_i - (\mu_{\gamma_i} + \sqrt{\rho\sigma_{\gamma_i}^2}v)}{\sqrt{(1-\rho)\sigma_{\gamma_i}^2}} \right) \right]^J \frac{e^{-v^2/2}}{2\pi} dv, \gamma_i \geq 0. \quad (3.24)$$

After some mathematical simplifications, we write (3.24) as

$$F_{\gamma_{\max_i}}^{\text{corr}}(\gamma_i) = \int_{-\infty}^{\infty} [\mathcal{Q}(\Theta v - \mathcal{Y}_{\gamma_i})]^J \frac{e^{-v^2/2}}{2\pi} dv, \gamma_i \geq 0. \quad (3.25)$$

In (3.25),  $\mathcal{Y}_{\gamma_i} = \frac{(\ln \gamma_i - \mu_{\gamma_i})}{\sqrt{\sigma_{\gamma_i}^2(1-\rho)}}$  and  $\Theta = \sqrt{\frac{\rho}{(1-\rho)}}$ . Further, utilizing (3.9) into (3.25), the closed-form solution of (3.25) can be approximated as

$$F_{\gamma_{\max_i}}^{\text{corr}}(\gamma_i) \approx \frac{2}{3} [\mathcal{Q}(-\mathcal{Y}_{\gamma_i})]^J + \frac{1}{6} \left[ \mathcal{Q}(\sqrt{3}\Theta - \mathcal{Y}_{\gamma_i}) \right]^J + \frac{1}{6} \left[ \mathcal{Q}(-\sqrt{3}\Theta - \mathcal{Y}_{\gamma_i}) \right]^J. \quad (3.26)$$

Now, similar to (3.13), the correlated ASC can be expressed as

$$\bar{\mathcal{C}}_s^{\text{corr}}(\gamma_M, \gamma_{\max}) = \sum_{i=1}^2 p_i \mathbb{E} \left[ \mathcal{C}_{s_i}^{\text{corr}}(\gamma_{M_i}, \gamma_{\max_i}) \right]. \quad (3.27)$$

In (3.27),  $\mathbb{E}[\mathcal{C}_{s_i}^{\text{corr}}(\gamma_{M_i}, \gamma_{\max_i})]$  is written as follows:

$$\begin{aligned}
\mathbb{E}[\mathcal{C}_{s_i}^{\text{corr}}(\gamma_{M_i}, \gamma_{\max_i})] &= \int_0^\infty \int_0^\infty \mathcal{C}_{s_i}(\gamma_{M_i}, \gamma_{\max_i}) f_{\gamma_{M_i}}(\gamma_{M_i}) f_{\gamma_{\max_i}}^{\text{corr}}(\gamma_{\max_i}) d\gamma_{\max_i} d\gamma_{M_i} \\
&= \int_0^\infty \ln(1 + \gamma_{M_i}) f_{\gamma_{M_i}}(\gamma_{M_i}) F_{\gamma_{\max_i}}^{\text{corr}}(\gamma_{M_i}) d\gamma_{M_i} \\
&\quad - \int_0^\infty \ln(1 + \gamma_{\max_i}) f_{\gamma_{\max_i}}^{\text{corr}}(\gamma_{\max_i}) [1 - F_{\gamma_{M_i}}(\gamma_{\max_i})] d\gamma_{\max_i} \\
&= \mathcal{C}_{M_i}^{\text{corr}}(\gamma_{M_i}) - \mathcal{C}_{\max_i}^{\text{corr}}(\gamma_{\max_i}).
\end{aligned} \tag{3.28}$$

In (3.28),

$$\mathcal{C}_{M_i}^{\text{corr}}(\gamma_{M_i}) = \int_0^\infty \ln(1 + \gamma_{M_i}) \left[ \frac{2}{3} [\mathcal{Q}(-\mathcal{Y}_{\gamma_i})]^J + \frac{1}{6} [\mathcal{Q}(\sqrt{3}\Theta - \mathcal{Y}_{\gamma_i})]^J + \frac{1}{6} [\mathcal{Q}(-\sqrt{3}\Theta - \mathcal{Y}_{\gamma_i})]^J \right] f(\gamma_{M_i}) d\gamma_{M_i}, \tag{3.29}$$

$$\mathcal{C}_{\max_i}^{\text{corr}}(\gamma_{\max_i}) = \int_0^\infty \ln(1 + \gamma_{\max_i}) \left[ \mathcal{Q}\left(\frac{\ln \gamma_{\max_i} - \mu_{\gamma_{M_i}}}{\sigma_{\gamma_{M_i}}}\right) \right]^J f_{\gamma_{\max_i}}^{\text{corr}}(\gamma_{\max_i}) d\gamma_{\max_i}. \tag{3.30}$$

Utilizing (3.9) into (3.29) and (3.30), the closed-form expressions for (3.29) and (3.30) can be obtained, respectively, as

$$\mathcal{C}_{k_i}^{\text{corr}}(\gamma_{k_i}) \approx \frac{2}{3} \Psi_{k_i}(\mu_{\gamma_{k_i}}) + \frac{1}{6} \Psi_{k_i}(\mu_{\gamma_{k_i}} + \sqrt{3}\sigma_{\gamma_{k_i}}) + \frac{1}{6} \Psi_{k_i}(\mu_{\gamma_{k_i}} - \sqrt{3}\sigma_{\gamma_{k_i}}). \tag{3.31}$$

In (3.31),  $k \in \{M, \max\}$ ,  $\Psi_{M_i}(x) = \ln(1 + \exp(x)) [0.66[\mathcal{Q}(-\mathcal{Y}_{\gamma_i}(x))]^J + 0.166[\mathcal{Q}(\sqrt{3}\Theta - \mathcal{Y}_{\gamma_i}(x))]^J + 0.166[\mathcal{Q}(-\sqrt{3}\Theta - \mathcal{Y}_{\gamma_i}(x))]^J]$ , and  $\Psi_{\max_i}(x) = \ln(1 + \exp(x)) [\mathcal{Q}((x - \mu_{\gamma_{M_i}}) / \sigma_{\gamma_{M_i}})]^J$ .

Finally, substituting (3.31) into (3.27), we can obtain the closed-form expression for the correlated ASC.

To provide further insights into the secrecy performance, let us now present some special cases as follows:

1.  **$J = 1, \rho = 0$ :** Let us consider the scenario when there is a single eavesdropper and there is no correlation between the eavesdropper channels. In this case, Eq. (3.27) can be simplified as

$$\bar{\mathcal{C}}_s(\gamma_M, \gamma_{e_1}) = \sum_{i=1}^2 p_i \mathbb{E}[\mathcal{C}_{s_i}(\gamma_{M_i}, \gamma_{e_{1i}})]. \tag{3.32}$$

Further, as we set the value of  $J = 1$  and  $\rho = 0$ , the terms in (3.29) and (3.30) become  $\mathcal{Y}_{\gamma_i} = \frac{(\ln \gamma_i - \mu_{\gamma_i})}{\sqrt{\sigma_{\gamma_i}^2}}$  and  $\Theta = 0$ . Consequently, (3.29) and (3.30) can be re-written as follows:

$$\mathcal{C}_{M_i}^{\text{corr}}(\gamma_{M_i}) = \int_0^\infty \ln(1 + \gamma_{M_i}) [1 - \mathcal{Q}(\mathcal{Y}_{\gamma_i})] f(\gamma_{M_i}) d\gamma_{M_i}. \tag{3.33}$$

$$\mathcal{C}_{e_{1i}}^{\text{corr}}(\gamma_{e_{1i}}) = \int_0^\infty \ln(1 + \gamma_{e_{1i}}) \left[ \mathcal{Q} \left( \frac{\ln \gamma_{e_{1i}} - \mu_{\gamma_{M_i}}}{\sigma_{\gamma_{M_i}}} \right) \right] f_{\gamma_{e_{1i}}}^{\text{corr}}(\gamma_{e_{1i}}) d\gamma_{e_{1i}}. \quad (3.34)$$

Utilizing (3.9) into (3.33) and (3.34), the closed-form expressions for (3.33) and (3.34) can be obtained similar to (3.31).

Finally, substituting the closed-form expressions of  $\mathcal{C}_{M_i}^{\text{corr}}(\gamma_{M_i})$  and  $\mathcal{C}_{e_{1i}}^{\text{corr}}(\gamma_{e_{1i}})$  from (3.33) and (3.34), respectively, into (3.32), the closed-form expression for the ASC can be obtained.

2.  $\mathbf{p} = \mathbf{1}, \mathbf{\rho} \neq \mathbf{0}$ : Let us consider the special case when only the impulsive noise is present and the eavesdroppers are correlated. For this case, (3.27) can be simplified as follows:

$$\bar{\mathcal{C}}_s^{\text{corr}}(\gamma_M, \gamma_{\max}) = \mathbb{E} \left[ \mathcal{C}_{s_2}^{\text{corr}}(\gamma_{M_2}, \gamma_{\max_2}) \right]. \quad (3.35)$$

Substituting (3.31) with  $i = 2$  into (3.35), the closed-form expression for the correlated ASC can be derived.

3.  $\mathbf{\rho} = \mathbf{0}, \mathbf{p} = \mathbf{1}, \mathbf{J} = \mathbf{1}$ : Let us take the special case when there is no correlation between the eavesdropper channels and only the impulsive noise and a single eavesdropper is present. For this case, (3.27) can be simplified as follows:

$$\bar{\mathcal{C}}_s^{\text{corr}}(\gamma_M, \gamma_{\max}) = \mathbb{E} \left[ \mathcal{C}_{s_2}^{\text{corr}}(\gamma_{M_2}, \gamma_{e_{12}}) \right]. \quad (3.36)$$

Finally, substituting (3.31) with  $k = e_1$  and  $i = 2$  into (3.36), the closed-form expression for the ASC can be evaluated.

**Remark 3.1.** In order to analyze the effect of  $\bar{\gamma}_M$ , we observe Eqs. (3.17) and (3.31). As  $\bar{\gamma}_M$  increases,  $\mu_{\gamma_M}$  increases due to which the terms  $\Psi_{k_i}(x)$  and  $\mathcal{C}_{k_i}(\gamma_{k_i})$  increase. Finally, the overall difference in Eqs. (3.14) and (3.28) increases. Hence, ASC of the considered system increases. This trend in the ASC curves will also be verified from Figs. 3.2 and 3.4 in Section 3.4.

**Remark 3.2.** To observe the effect of parameters  $J$  and  $K$ , we carefully observe Eqs. (3.17) and (3.31). For the higher value of  $J$  and  $K$ ,  $\Psi_{k_i}(x)$  always decreases and as a consequence, the overall value of  $\mathcal{C}_{k_i}(\gamma_{k_i})$  becomes less. Hence, the overall ASC of considered system decreases. This decreasing trend of the ASC curves is corroborated from Figs. 3.2 and 3.4 in Section 3.4.

**Remark 3.3.** From Eq. (3.27), it is noted that any non-zero value of  $p$  indicates the presence of impulsive noise. Further, as the value of  $p$  increases, the total sum of both the terms  $\mathbb{E}[\mathcal{C}_{s_1}^{\text{corr}}(\gamma_{M_1}, \gamma_{\max_1})]$  and  $\mathbb{E}[\mathcal{C}_{s_2}^{\text{corr}}(\gamma_{M_2}, \gamma_{\max_2})]$  in Eq. (3.27) start decreasing. Thereafter, as the value of  $p$  becomes 1, the contribution of the term  $\mathbb{E}[\mathcal{C}_{s_1}^{\text{corr}}(\gamma_{M_1}, \gamma_{\max_1})]$  becomes zero and only the term  $\mathbb{E}[\mathcal{C}_{s_2}^{\text{corr}}(\gamma_{M_2}, \gamma_{\max_2})]$  remains. Hence, the overall value of the ASC reduces with  $p$ . This analysis is also justified from Fig. 3.2 in Section 3.4.

**Remark 3.4.** Let us examine Eq. (3.31), from where it is observed that as the value of  $\rho$  increases,  $\Psi_{M_i}(x)$  increases. As a result,  $\mathcal{C}_{M_i}^{\text{corr}}(\gamma_{M_i})$  tends to increase. Further,  $\Psi_{\max_i}(x)$  remains constant because it does not depend upon  $\rho$ . Therefore, in Eq. (3.28), the overall difference tends to increase. This analysis is also justified from Fig. 3.4 in Section 3.4.

### 3.3.3 Computation of SOP

1) Case-I, When the main channel and eavesdropper channels are IID:

The SOP is one of the functional and widely used performance metrics of the PLS study, which

ascertain the probability that the instantaneous achievable secrecy capacity falls below a target secrecy capacity threshold ( $\mathcal{C}_{\text{th}}$ ). The SOP for the proposed PLC system can be expressed as

$$\mathcal{P}_{\text{sop}}(\mathcal{C}_{\text{th}}) = \sum_{i=1}^2 p_i \mathcal{P}_{\text{out}_i}(\mathcal{C}_{\text{th}}). \quad (3.37)$$

In (3.37),  $\mathcal{P}_{\text{out}_i}(\mathcal{C}_{\text{th}})$  is defined as

$$\begin{aligned} \mathcal{P}_{\text{out}_i}(\mathcal{C}_{\text{th}}) &= \Pr [\mathcal{C}_s(\gamma_{M_i}, \gamma_{\max_i}) < \mathcal{C}_{\text{th}}] \\ &= \Pr [\gamma_{M_i} < \lambda \gamma_{\max_i} + \lambda - 1]. \end{aligned} \quad (3.38)$$

In (3.38),  $\lambda = \exp(\mathcal{C}_{\text{th}})$ , Further, deriving exact closed-form SOP expression from (3.38) is intractable. Therefore, we proceed with computing the lower bound on SOP, that is,  $(\lambda \gamma_{\max_i} + \lambda - 1) \approx \lambda \gamma_{\max_i}$ . As a result, (3.38) is approximated as

$$\begin{aligned} \mathcal{P}_{\text{out}_i}(\mathcal{C}_{\text{th}}) &\approx 1 - \Pr \left[ \gamma_{\max_i} < \frac{\gamma_{M_i}}{\lambda} \right] \\ &= 1 - \int_0^\infty F_{\gamma_{\max_i}} \left( \frac{\gamma_{M_i}}{\lambda} \right) f_{\gamma_{M_i}}(\gamma_{M_i}) d\gamma_{M_i} \\ &= 1 - \mathcal{C}'_{M_i}(\gamma_{M_i}). \end{aligned} \quad (3.39)$$

In (3.39),

$$\mathcal{C}'_{M_i}(\gamma_{M_i}) = \int_0^\infty \left[ 1 - \mathcal{Q} \left( \frac{\ln(\frac{\gamma_{M_i}}{\lambda}) - \mu_{\gamma_{\max_i}}}{\sigma_{\gamma_{\max_i}}} \right) \right]^J f(\gamma_{M_i}) d\gamma_{M_i}. \quad (3.40)$$

Utilizing (3.9) into (3.40), the closed-form solution for (3.40) can be computed as

$$\mathcal{C}'_{M_i}(\gamma_{M_i}) \approx \frac{2}{3} \Psi_{M_i}(\mu_{\gamma_{M_i}}) + \frac{1}{6} \Psi_{M_i}(\mu_{\gamma_{M_i}} + \sqrt{3} \sigma_{\gamma_{M_i}}) + \frac{1}{6} \Psi_{M_i}(\mu_{\gamma_{M_i}} - \sqrt{3} \sigma_{\gamma_{M_i}}). \quad (3.41)$$

In (3.41),  $\Psi_{M_i}(x) = [1 - \mathcal{Q}((x - \mu_{\gamma_{\max_i}})/\sigma_{\gamma_{\max_i}})]^J$ .

Finally, substituting (3.41) into (3.37), the closed-form expression for the SOP can be evaluated.

2) *Case-II, When all the eavesdropper channels are correlated but independent of main channel:*

Similar to (3.37), the correlated SOP can be written as

$$\mathcal{P}_{\text{sop}}^{\text{corr}}(\mathcal{C}_{\text{th}}) = \sum_{i=1}^2 p_i \mathcal{P}_{\text{out}_i}^{\text{corr}}(\mathcal{C}_{\text{th}}). \quad (3.42)$$

In (3.42),  $\mathcal{P}_{\text{out}_i}^{\text{corr}}(\mathcal{C}_{\text{th}})$  is given by

$$\begin{aligned} \mathcal{P}_{\text{out}_i}^{\text{corr}}(\mathcal{C}_{\text{th}}) &\approx 1 - \int_0^\infty F_{\gamma_{\max_i}}^{\text{corr}} \left( \frac{\gamma_{M_i}}{\lambda} \right) f_{\gamma_{M_i}}(\gamma_{M_i}) d\gamma_{M_i} \\ &\approx 1 - \mathcal{C}_{M_i}^{\text{corr}'}(\gamma_{M_i}). \end{aligned} \quad (3.43)$$

In (3.43),

$$\mathcal{C}_{M_i}^{\text{corr}'}(\gamma_{M_i}) = \int_0^\infty \left[ \frac{2}{3} [\mathcal{Q}(-\mathcal{Y}_{\gamma_i})]^J + \frac{1}{6} [\mathcal{Q}(\sqrt{3}\Theta - \mathcal{Y}_{\gamma_i})]^J + \frac{1}{6} [\mathcal{Q}(-\sqrt{3}\Theta - \mathcal{Y}_{\gamma_i})]^J \right] f(\gamma_{M_i}) d\gamma_{M_i}. \quad (3.44)$$

Utilizing (3.9) into (3.44), the closed-form expressions for (3.44) can be calculated as

$$\mathcal{C}_{M_i}^{\text{corr}'}(\gamma_{M_i}) \approx \frac{2}{3}\Psi_{M_i}(\mu_{\gamma_{M_i}}) + \frac{1}{6}\Psi_{M_i}(\mu_{\gamma_{M_i}} + \sqrt{3}\sigma_{\gamma_{M_i}}) + \frac{1}{6}\Psi_{M_i}(\mu_{\gamma_{M_i}} - \sqrt{3}\sigma_{\gamma_{M_i}}). \quad (3.45)$$

In (3.45),  $\Psi_{M_i}(x) = 0.66 [\mathcal{Q}(-\mathcal{Y}_{\gamma_i}(x))]^J + 0.166 [\mathcal{Q}(\sqrt{3}\Theta - \mathcal{Y}_{\gamma_i}(x))]^J + 0.166 [\mathcal{Q}(-\sqrt{3}\Theta - \mathcal{Y}_{\gamma_i}(x))]^J$ .

Finally, substituting (3.45) into (3.42), the closed-form expression for the correlated SOP can be evaluated.

Let us now also present some special cases for the derived SOP expressions to gain further insights.

1.  $\mathbf{J} = \mathbf{1}, \boldsymbol{\rho} = \mathbf{0}$ : In this case, the terms in (3.44) become  $\mathcal{Y}_{\gamma_i} = \frac{(\ln \gamma_i - \mu_{\gamma_i})}{\sqrt{\sigma_{\gamma_i}^2}}$  and  $\Theta = 0$ . Consequently, (3.44) can be re-written as follows:

$$\mathcal{C}_{M_i}^{\text{corr}'}(\gamma_{M_i}) = \int_0^\infty [\mathcal{Q}(-\mathcal{Y}_{\gamma_i})] f(\gamma_{M_i}) d\gamma_{M_i} = \mathbb{E}[1 - \mathcal{Q}(\mathcal{Y}_{\gamma_i})]. \quad (3.46)$$

Utilizing (3.9) into (3.46), the closed-form expressions for  $\mathcal{C}_{M_i}^{\text{corr}'}(\gamma_{M_i})$  can be calculated as

$$\mathcal{C}_{M_i}^{\text{corr}'}(\gamma_{M_i}) \approx \frac{2}{3}\Psi_{M_i}(\mu_{\gamma_{M_i}}) + \frac{1}{6}\Psi_{M_i}(\mu_{\gamma_{M_i}} + \sqrt{3}\sigma_{\gamma_{M_i}}) + \frac{1}{6}\Psi_{M_i}(\mu_{\gamma_{M_i}} - \sqrt{3}\sigma_{\gamma_{M_i}}). \quad (3.47)$$

In (3.47)  $\Psi_{M_i}(x) = [1 - \mathcal{Q}(\mathcal{Y}_{\gamma_i}(x))]$ .

Finally, substituting (3.47) into (3.42), the closed-form expression for the SOP can be computed.

2.  $\mathbf{p} = \mathbf{1}, \boldsymbol{\rho} \neq \mathbf{0}$ : For this case, (3.42) can be simplified as follows:

$$\mathcal{P}_{\text{sop}}^{\text{corr}}(\mathcal{C}_{\text{th}}) = \mathcal{P}_{\text{out}_2}^{\text{corr}}(\mathcal{C}_{\text{th}}). \quad (3.48)$$

Substituting (3.45) with  $i = 2$  into (3.48), the closed-form expression for the correlated SOP can be derived.

3.  $\boldsymbol{\rho} = \mathbf{0}, \mathbf{p} = \mathbf{1}, \mathbf{J} = \mathbf{1}$ : Let us consider the special case when there is no correlation between eavesdropper channels and only the impulsive noise and a single eavesdropper is present. For this case, (3.42) can be deduced as follows:

$$\mathcal{P}_{\text{sop}}^{\text{corr}}(\mathcal{C}_{\text{th}}) = \mathcal{P}_{\text{out}_2}^{\text{corr}}(\mathcal{C}_{\text{th}}). \quad (3.49)$$

Using (3.45) with  $i = 2$  into (3.49), the closed-form expression for the SOP can be derived.

**Remark 3.5.** *The ASC and SOP results corresponding to the special case  $J = 1, \rho = 0$  were also reported in [Mohan et al., 2019]. Therefore, the results derived in this work are very generalized of which [Mohan et al., 2019] forms a special case.*

**Remark 3.6.** *Akin to Remark 3.1 to Remark 3.4, a similar theoretical analysis can be conducted to analyze the trend of the various parameters on the SOP performance.*

### 3.3.4 Asymptotic SOP Analysis

In order to comprehensively investigate the secrecy performance, we study the asymptotic behavior of the SOP in the high SNR regime. In this context, we analyze Eq. (3.45) for high average SNR on the main channel; as  $\bar{\gamma}_M \rightarrow \infty$ , the terms in Eq. (3.45) can be approximated. For instance,  $\Psi_{M_i}(\mu_{\gamma_{M_i}} + \sqrt{3}\sigma_{\gamma_{M_i}}) \approx \Psi_{M_i}(\mu_{\gamma_{M_i}})$  and  $\Psi_{M_i}(\mu_{\gamma_{M_i}} - \sqrt{3}\sigma_{\gamma_{M_i}}) \approx \Psi_{M_i}(\mu_{\gamma_{M_i}})$ . Likewise,  $[\mathcal{Q}(\sqrt{3}\Theta - \mathcal{Y}_{\gamma_i}(x))]^J \approx [\mathcal{Q}(-\mathcal{Y}_{\gamma_i}(x))]^J$  and  $[\mathcal{Q}(-\sqrt{3}\Theta - \mathcal{Y}_{\gamma_i}(x))]^J \approx [\mathcal{Q}(-\mathcal{Y}_{\gamma_i}(x))]^J$ . Hence, (3.45) can be re-written as Hence, (3.45) can be re-written as

$$\mathcal{C}_{M_i}^{\text{corr}'}(\gamma_{M_i}) \approx \Psi_{M_i}(\mu_{\gamma_{M_i}}). \quad (3.50)$$

In (3.50),  $\Psi_{M_i}(x) = [\mathcal{Q}(-\mathcal{Y}_{\gamma_i}(x))]^J$ . Further, in (3.50) the Gaussian  $\mathcal{Q}$ -function can be upper bounded as

$$[\mathcal{Q}(-\mathcal{Y}_{\gamma_i}(x))]^j \leq \left[ -\frac{1}{2} \exp\left(\frac{-(\mathcal{Y}_{\gamma_i}(x))^2}{2}\right) \right]^j. \quad (3.51)$$

Finally, using (3.51) into (3.50) and substituting (3.50) into (3.42), the closed-form expression of the asymptotic SOP can be computed.

### 3.3.5 Secrecy Throughput Optimization

In this subsection, we formulate an algorithm to maximize the secrecy throughput for the considered PLC system under security and reliability constraints.

To guarantee secure communication, we assume the Wyner's wiretap encoding scheme for the considered system model, where  $A$  transmits information at the rate of  $\mathcal{R}_M$  to  $M$  by maintaining a threshold secrecy rate  $\mathcal{R}_{\text{th}}$  against eavesdroppers,  $E = \{e_j | j = 1, 2, \dots, J\}$ . The net rate redundancy  $\mathcal{R}_d = \mathcal{R}_M - \mathcal{R}_{\text{th}}$ , predicts the cost of secure communication against multiple eavesdropping. Under perfect secrecy conditions, the main channel ( $A$  to  $M$  link) must follow the condition  $\mathcal{C}_M > \mathcal{R}_{\text{th}}$  where  $\mathcal{C}_M$  is the instantaneous channel capacity of  $M$ . Whereas, perfect secrecy fails when  $\mathcal{C}_E > \mathcal{R}_d$ , where  $\mathcal{C}_E$  is the instantaneous channel capacity of  $E$ . Hence, we express the SOP as the conditional probability [Zhou *et al.*, 2011]

$$\mathcal{P}_{\text{csop}}^{\text{corr}} \triangleq \Pr(\mathcal{C}_E > \mathcal{R}_M - \mathcal{R}_{\text{th}} | \text{data transmission}). \quad (3.52)$$

Using (3.52), the overall conditional SOP of the considered system can be expressed as

$$\mathcal{P}_{\text{csop}}^{\text{corr}} = \sum_{i=1}^2 p_i \mathcal{P}_{\text{cout}_i}^{\text{corr}}. \quad (3.53)$$

In (3.53),  $\mathcal{P}_{\text{cout}_i}^{\text{corr}}$  denotes the instantaneous conditional SOP for the  $i^{\text{th}}$  component.

Now, our objective is to maximize the secrecy throughput for the considered PLC system. The secrecy throughput is defined as [Zhou *et al.*, 2011]

$$\tau = \mathcal{P}_{\text{tx}} \mathcal{R}_{\text{th}}. \quad (3.54)$$

In (3.54),  $\mathcal{P}_{\text{tx}}$  denotes the probability of transmission. Hence, the optimization problem can be formulated as

$$\max \eta, \quad \text{s.t. } \mathcal{P}_{\text{csop}}^{\text{corr}} \leq \varrho, \mathcal{P}_{\text{tx}} \geq v. \quad (3.55)$$

In (3.55),  $\varrho \in [0, 1]$  and  $v \in [0, 1]$  represent the constraints for secure and reliable transmission, respectively. Further, we assume that the data transmission is possible whenever the value of  $\gamma_{M_i}$

is greater than a certain threshold SNR,  $\gamma_{\text{th}}$ , with  $\gamma_{\text{th}} \geq \exp(\mathcal{R}_{\text{th}}) - 1$ . Hence, the transmission probability can be expressed as

$$\mathcal{P}_{\text{tx}} = \Pr(\gamma_{M_i} > \gamma_{\text{th}}) = 1 - \mathcal{Q}\left(\frac{\ln \gamma_{\text{th}} - \mu_{\gamma_{M_i}}}{\sigma_{\gamma_{M_i}}}\right). \quad (3.56)$$

Let us compute  $\mathcal{P}_{\text{cout}_i}^{\text{corr}}$  as follows:

$$\begin{aligned} \mathcal{P}_{\text{cout}_i}^{\text{corr}} &= \Pr(\mathcal{C}_E > \mathcal{C}_M | \gamma_{M_i} > \gamma_{\text{th}}) \\ &= \frac{\Pr(\gamma_{\text{th}} < \gamma_{M_i} < \lambda(1 + \gamma_{\text{max}_i}) - 1)}{\Pr(\gamma_{M_i} > \gamma_{\text{th}})}. \end{aligned} \quad (3.57)$$

Now, taking the lower bound in (3.57), i.e.,  $\lambda(\gamma_{E_i} + 1) - 1 \approx \lambda\gamma_{E_i}$ , we get

$$\begin{aligned} \mathcal{P}_{\text{cout}_i}^{\text{corr}} &\approx \frac{1 - \Pr(\gamma_{\text{th}} < \gamma_{M_i} < \lambda\gamma_{\text{max}_i})}{\Pr(\gamma_{M_i} > \gamma_{\text{th}})} \\ &\approx \frac{\int_{\Theta}^{\infty} \int_{\gamma_{\text{th}}}^{\lambda\gamma_{\text{max}_i}} f_{\gamma_{M_i}}(\gamma_{M_i}) f_{\gamma_{\text{max}_i}}(\gamma_{\text{max}_i}) d\gamma_{M_i} d\gamma_{\text{max}_i}}{\Pr(\gamma_{M_i} > \gamma_{\text{th}})}. \end{aligned} \quad (3.58)$$

In (3.58),  $\Theta = \left(\frac{1+\gamma_{\text{th}}}{\lambda} - 1\right)$ . Further, the double integration of (3.58) can be divided into two parts as follows:

$$\mathcal{I} = \underbrace{\int_{\Theta}^{\infty} \int_0^{\lambda\gamma_{\text{max}_i}} f_{\gamma_{M_i}}(\gamma_{M_i}) f_{\gamma_{\text{max}_i}}(\gamma_{\text{max}_i}) d\gamma_{M_i} d\gamma_{E_j}}_{\mathcal{I}_{1,i}} - \underbrace{\int_{\Theta}^{\infty} \int_0^{\gamma_{\text{th}}} f_{\gamma_{M_i}}(\gamma_{M_i}) f_{\gamma_{\text{max}_i}}(\gamma_{\text{max}_i}) d\gamma_{M_i} d\gamma_{E_j}}_{\mathcal{I}_{2,i}}. \quad (3.59)$$

By substituting (3.7) and (3.12) into (3.59), the integrals  $\mathcal{I}_{1,i}$  and  $\mathcal{I}_{2,i}$  can be expressed as

$$\begin{aligned} \mathcal{I}_{1,i} &= J \int_{\Theta}^{\infty} \mathcal{Q}\left(\frac{\mu_{\gamma_{M_i}} - \ln(\lambda\gamma_{\text{max}_i})}{\sigma_{\gamma_{M_i}}}\right) \left[ \mathcal{Q}\left(\frac{\mu_{\gamma_{\text{max}_i}} - \ln \gamma_{\text{max}_i}}{\sigma_{\gamma_{\text{max}_i}}}\right) \right]^{J-1} \\ &\quad \times \frac{1}{\gamma_{\text{max}_i} \sqrt{2\pi\sigma_{\gamma_{\text{max}_i}}^2}} \exp\left(-\frac{(\ln \gamma_{\text{max}_i} - \mu_{\gamma_{\text{max}_i}})^2}{2\sigma_{\gamma_{\text{max}_i}}^2}\right) d\gamma_{\text{max}_i}. \end{aligned} \quad (3.60)$$

$$\begin{aligned} \mathcal{I}_{2,i} &= J \int_{\Theta}^{\infty} \mathcal{Q}\left(\frac{\mu_{\gamma_{M_i}} - \ln(\gamma_{\text{th}})}{\sigma_{\gamma_{M_i}}}\right) \left[ \mathcal{Q}\left(\frac{\mu_{\gamma_{\text{max}_i}} - \ln \gamma_{\text{max}_i}}{\sigma_{\gamma_{\text{max}_i}}}\right) \right]^{J-1} \\ &\quad \times \frac{1}{\gamma_{\text{max}_i} \sqrt{2\pi\sigma_{\gamma_{\text{max}_i}}^2}} \exp\left(-\frac{(\ln \gamma_{\text{max}_i} - \mu_{\gamma_{\text{max}_i}})^2}{2\sigma_{\gamma_{\text{max}_i}}^2}\right) d\gamma_{\text{max}_i}. \end{aligned} \quad (3.61)$$

Further, applying Gaussian  $\mathcal{Q}$ -function approximation given by (3.51) into (3.60), we obtain

$$\mathcal{I}_{1,i} = \frac{J \exp(-\mathcal{K}_3)}{\gamma_{\text{max}_i} \sqrt{2\pi\sigma_{\gamma_{\text{max}_i}}^2}} \int_{\Theta}^{\infty} \exp[-\mathcal{K}_1(\ln \gamma_{\text{max}_i})^2 + (2\mathcal{K}_2 \ln \gamma_{\text{max}_i})] d\gamma_{\text{max}_i}. \quad (3.62)$$

In (3.62),  $\mathcal{K}_1 = (\mathcal{C}_1 + \mathcal{C}_2 + \mathcal{C}_3)$ ,  $\mathcal{K}_2 = (\mathcal{C}_1 \mu_{\gamma_{\max_i}} + \mathcal{C}_2 \mu_{\gamma_{\max_i}} + \mathcal{C}_3 \mu_{\gamma_{M_i}} - \mathcal{C}_3 \log \lambda)$ , and  $\mathcal{K}_3 = [\mathcal{C}_1 (\mu_{\gamma_{\max_i}})^2 + \mathcal{C}_2 (\mu_{\gamma_{\max_i}})^2 + \mathcal{C}_3 (\mu_{\gamma_{M_i}})^2 + \mathcal{C}_3 \log \lambda - 2\mathcal{C}_3 \log \lambda \mu_{\gamma_{M_i}}]$ , where  $\mathcal{C}_1 = 1/\sigma_{\gamma_{\max_i}}^2$ ,  $\mathcal{C}_2 = (J-1)/(2\sigma_{\gamma_{\max_i}}^2)$ , and  $\mathcal{C}_3 = 1/(2\sigma_{\gamma_{M_i}}^2)$ . Finally, the closed-form expression for  $\mathcal{I}_{1,i}$  can be written as

$$\mathcal{I}_{1,i} = \frac{J \exp\left(-\mathcal{K}_3 - \frac{\sqrt{\mathcal{K}_1} \mathcal{K}_2}{\mathcal{K}_1^2}\right)}{\sqrt{2\mathcal{K}_1} \sigma_{\gamma_{\max_i}}} \mathcal{Q}\left(\sqrt{2\mathcal{K}_1} \ln \gamma_{\max_i} - \frac{\sqrt{2\mathcal{K}_2}}{\sqrt{\mathcal{K}_1}}\right). \quad (3.63)$$

Following a similar approach that we have used to compute  $\mathcal{I}_{1,i}$ ,  $\mathcal{I}_{2,i}$  is obtained as

$$\mathcal{I}_{2,i} = \frac{J}{\sqrt{2}} \mathcal{Q}\left(\frac{\mu_{\gamma_{M_i}} - \ln \gamma_{\text{th}}}{\sigma_{\gamma_{M_i}}}\right) \mathcal{Q}\left[\frac{\sqrt{2}(\ln \gamma_{\max_i} - \mu_{\gamma_{\max_i}})}{\sigma_{\gamma_{\max_i}}}\right]. \quad (3.64)$$

Thus, substituting (2.45), (3.63), and (3.64) into (2.47), the closed-form expression of  $\mathcal{P}_{\text{cout}_i}^{\text{corr}}$  can be obtained. Then, inserting (2.47) into (3.53) the closed-form expression of the conditional SOP can be derived.

Now, to maximize the secrecy throughput, we find the optimal value of  $\gamma_{\text{th}}$  for the considered optimization problem as follows:

$$\arg \max_{\gamma_{\text{th}}} \mathcal{P}_{\text{tx}}(\gamma_{\text{th}}) \mathcal{R}_{\text{th}}, \quad (3.65a)$$

$$\text{s.t. } \mathcal{P}_{\text{csop}}^{\text{corr}}(\gamma_{\text{th}}, \mathcal{R}_{\text{th}}) \leq \varrho, \quad \mathcal{P}_{\text{tx}}(\gamma_{\text{th}}) \geq v, \quad (3.65b)$$

$$\gamma_{\text{th}} \geq \exp(\mathcal{R}_{\text{th}}) - 1, \quad \mathcal{R}_{\text{th}} > 0. \quad (3.65c)$$

In (3.65a)-(3.65c),  $\mathcal{P}_{\text{tx}}$  and  $\mathcal{P}_{\text{csop}}^{\text{corr}}$  are a function of  $\gamma_{\text{th}}$  and  $\mathcal{R}_{\text{th}}$ . Therefore, using (3.56) the possible range of  $\gamma_{\text{th}}$  is obtained by following  $\mathcal{P}_{\text{tx}}(\gamma_{\text{th}}) \geq v$ . Thus,  $\gamma_{\text{th}} \in [\exp(\mathcal{R}_{\text{th}}) - 1, \gamma_{\text{th}}^u]$ , where  $\gamma_{\text{th}}^u$  is the upper limit of  $\gamma_{\text{th}}$  calculated from (2.45). Herein, to maximize the secrecy throughput the smallest value of  $\gamma_{\text{th}}$  is considered while satisfying the security constraints. Since, (3.53) is a decreasing function of  $\gamma_{\text{th}}$ , the optimal  $\gamma_{\text{th}}$  can be obtained using  $\mathcal{P}_{\text{csop}}^{\text{corr}}(\gamma_{\text{th}}, \mathcal{R}_{\text{th}}) = \varrho$ , by following  $\mathcal{P}_{\text{csop}}^{\text{corr}}(\gamma_{\text{th}}, \mathcal{R}_{\text{th}}) \leq \varrho$ , as

$$\gamma_{\text{th}} = \begin{cases} \exp(\mathcal{R}_{\text{th}}) - 1, & \text{if } \mathcal{R}_{\text{th}} \leq \ln \frac{\bar{\gamma}_M \varrho}{\bar{\gamma}_{\max}(1-\varrho)}, \\ \gamma_{\text{th}}^u, & \text{otherwise.} \end{cases} \quad (3.66)$$

In (3.66),  $\gamma_{\text{th}}^u$  denotes the upper limit of  $\gamma_{\text{th}}$ . It should be noted that the optimal value of  $\gamma_{\text{th}}$  given by (3.53) and (3.56) is calculated using MATLAB software for mathematical tractability. The algorithm to compute the optimal value of  $\gamma_{\text{th}}$  that maximizes the secrecy throughput is summarized as Algorithm 3.3.1 at top of next page.

### 3.3.6 Computation of SPSC

SPSC is a fundamental benchmark in the PLS study, which ascertains the probability of non-zero secrecy capacity. Mathematically, the SPSC of the considered PLC system can be expressed as

$$\mathcal{P}_{\text{spsc}}^{\text{corr}} = \sum_{i=1}^2 p_i \mathcal{P}_{\text{spsc}_i}(\gamma_{M_i}, \gamma_{\max_i}). \quad (3.67)$$

In (3.67),  $\mathcal{P}_{\text{spsc}_i}(\gamma_{M_i}, \gamma_{\max_i})$  is defined as

$$\begin{aligned} \mathcal{P}_{\text{spsc}_i}^{\text{corr}}(\gamma_{M_i}, \gamma_{\max_i}) &= \Pr [\mathcal{C}_s(\gamma_{M_i}, \gamma_{\max_i}) > 0] \\ &= \int_0^\infty F_{\gamma_{\max_i}}(\gamma_{M_i}) f_{\gamma_{M_i}}(\gamma_{M_i}) d\gamma_{M_i} \\ &= \mathcal{C}_{M_i}^{\text{corr}''}(\gamma_{M_i}). \end{aligned} \quad (3.68)$$

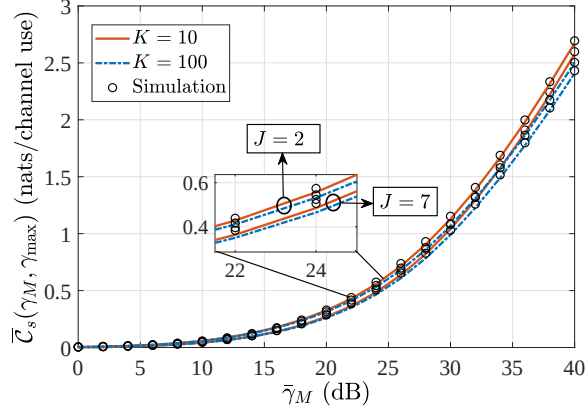


**Figure 3.2:** ASC over IID Log-normal PLC channels as a function of  $\bar{\gamma}_M$  for different values of  $K$  and  $J$ .

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**Algorithm 3.3.1:** Algorithm for finding the optimal  $\gamma_{\text{th}}$  to maximize the secrecy throughput

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- 1 *Initialization:*  $\mathcal{R}_{\text{th}}$ ,  $\varrho$ , and  $v$ ;
  - 2 Formulate optimization problem given in (3.55) and obtain  $\mathcal{P}_{\text{csop}}^{\text{corr}}$  and  $\mathcal{P}_{\text{tx}}$  given in (3.53) and (3.56), respectively;
  - 3 To maximize  $\eta$ , we aim to find the optimal value of  $\gamma_{\text{th}}$  for the considered design problem given in (3.65b) and (3.65c);
  - 4 **do**
  - 5   | Calculate  $\gamma_{\text{th}}$  by (3.56)
  - 6 **while**  $\mathcal{P}_{\text{tx}}(\gamma_{\text{th}}) \geq v$ ,  $\gamma_{\text{th}} \geq \exp(\mathcal{R}_{\text{th}}) - 1$ , and  $\mathcal{R}_{\text{th}} > 0$ ;
  - 7 Find optimal value of  $\gamma_{\text{th}}$ ;
  - 8 **do**
  - 9   | Calculate  $\gamma_{\text{th}}$  using expression  $\mathcal{P}_{\text{csop}}^{\text{corr}}(\gamma_{\text{th}}, \mathcal{R}_{\text{th}}) = \varrho$
  - 10 **while**  $\mathcal{P}_{\text{csop}}^{\text{corr}}(\gamma_{\text{th}}, \mathcal{R}_{\text{th}}) \leq \varrho$ ;
  - 11 Finally, a feasible range of optimal  $\gamma_{\text{th}}$  is given by (3.66);
- 

In (3.68),

$$\mathcal{C}_{M_i}^{\text{corr}''}(\gamma_{M_i}) = \int_0^\infty \left[ \frac{2}{3} [\mathcal{Q}(-\mathcal{Y}_{\gamma_i})]^J + \frac{1}{6} [\mathcal{Q}(\sqrt{3}\Theta - \mathcal{Y}_{\gamma_i})]^J + \frac{1}{6} [\mathcal{Q}(-\sqrt{3}\Theta - \mathcal{Y}_{\gamma_i})]^J \right] f(\gamma_{M_i}) d\gamma_{M_i}. \quad (3.69)$$

Utilizing (3.9) into (3.67), the closed-form solution for (3.67) can be computed as

$$\mathcal{C}_{M_i}^{\text{corr}''}(\gamma_{M_i}) \approx \frac{2}{3} \Psi_{M_i}(\mu_{\gamma_{M_i}}) + \frac{1}{6} \Psi_{M_i}(\mu_{\gamma_{M_i}} + \sqrt{3}\sigma_{\gamma_{M_i}}) + \frac{1}{6} \Psi_{M_i}(\mu_{\gamma_{M_i}} - \sqrt{3}\sigma_{\gamma_{M_i}}). \quad (3.70)$$

In (3.70),  $\Psi_{M_i}(x) = 0.66 [\mathcal{Q}(-\mathcal{Y}_{\gamma_i}(x))]^J + 0.166 [\mathcal{Q}(\sqrt{3}\Theta - \mathcal{Y}_{\gamma_i}(x))]^J + 0.166 [\mathcal{Q}(-\sqrt{3}\Theta - \mathcal{Y}_{\gamma_i}(x))]^J$ .

Finally, substituting (3.70) into (3.67), the closed-form expression for the correlated SPSC can be evaluated.

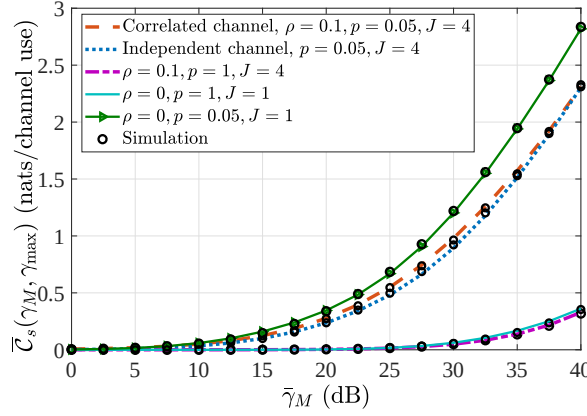


**Figure 3.3:** ASC versus  $\bar{\gamma}_M$  for different channel scenarios.

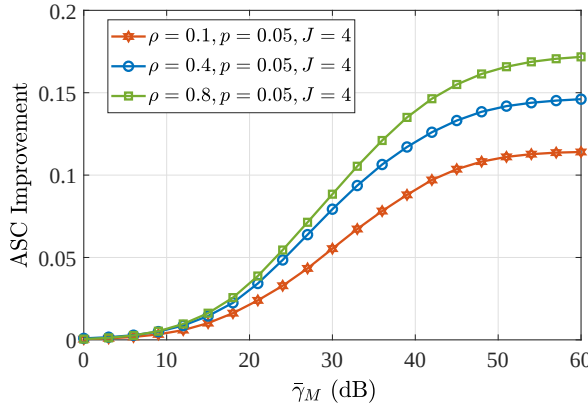


**Figure 3.4:** ASC improvement versus  $\bar{\gamma}_M$  for different values of  $\rho$ .

### 3.4 Numerical Results and Discussion

This section presents a detailed discussion of the analytical results of the considered PLC system. The analytical results are plotted using the derived mathematical expressions in the previous sections. Further, to comprehensively investigate the secrecy performance, the impact of the various parameters on the proposed PLC system model is noticed and discussed. The numerical and simulations results are obtained in MATLAB 2021a software using Monte Carlo simulations.

In Fig. 3.2, the ASC is plotted as a function of  $\bar{\gamma}_M$  for different values of  $K$  and  $J$ , when all the PLC channels are IID. The other parameters are set to  $p = 0.1$ ,  $D_M = D_{\max} = 0.3$  km,  $\beta = 32$ ,  $P_L = 60$  dB/km, and  $\bar{\gamma}_{\max} = 5$  dB. It can be observed that as the value of  $K$  increases, the ASC performance is decreased. The parameter  $K$  denotes the power of the impulsive noise component in Bernoulli-Gaussian noise, which implies that increasing the impulsive noise power with respect to the background noise power degrades the ASC performance gradually. Further, it can also be noticed from the figure that the ASC performance is improving with decreasing the number of eavesdroppers and vice versa. This means that the ASC of the considered PLC system will always reduce when the number of eavesdroppers increases.

Figure 3.3 demonstrates the behavior of ASC as a function of  $\bar{\gamma}_M$  for different channel scenarios, when  $\rho = 0, 0.1$ ,  $J = 1, 4$ ,  $p = 0.05, 1$ ,  $K = 100$ ,  $D_M = D_{\max} = 0.3$  km,  $\beta = 32$ , and  $P_L = 50$  dB/km. It can be noticed in the figure that the ASC performance of the considered

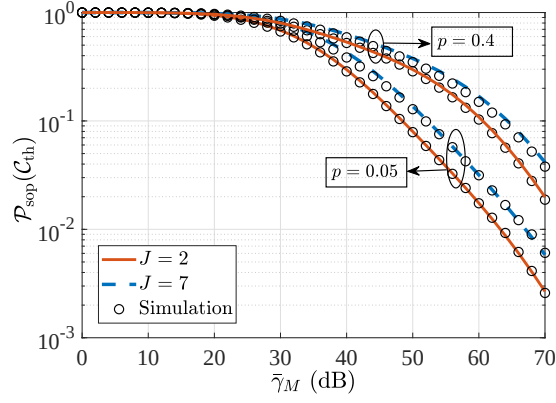


**Figure 3.5:** SOP over IID Log-normal PLC channels as a function of  $\bar{\gamma}_M$  for different values of  $p$  and  $J$ .

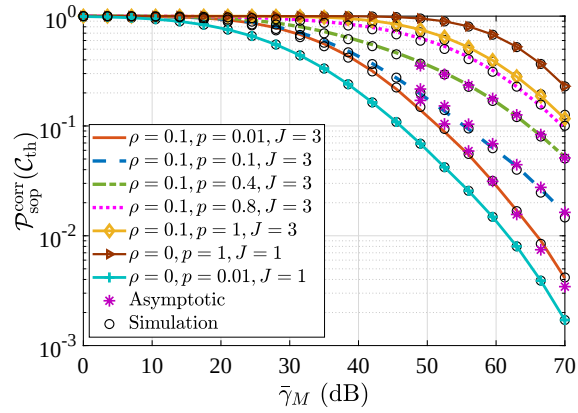


**Figure 3.6:** SOP versus  $\bar{\gamma}_M$  for different values of  $\rho$ ,  $p$ , and  $J$ .

PLC system improves with increasing  $\bar{\gamma}_M$ , when the eavesdropper channels are correlated. On the contrary, the ASC performance is low when all the channels are independent. This implies that the correlation among the multiple eavesdroppers makes the channel condition worse than the independent channel scenario, which helps improve the ASC of the considered PLC system. To give more insights into the ASC performance of the considered PLC system, we also plot the curves corresponding to the special cases given by (3.32)-(3.36). It can be seen from the figure that as  $\rho$  becomes zero and the number of eavesdroppers decreases to  $J = 1$ , the ASC performance improves. This is quite intuitive as the deteriorating effect on ASC reduces with the decrease in the number of eavesdroppers and correlation coefficient. We also observe from the figure that the ASC performance decreases drastically as  $p$  increases from 0.05 to 1. This indicates that the heavy occurrence of impulsive noise components severely degrades the ASC performance of the considered PLC system.

Figure 3.4 shows the ASC improvement versus  $\bar{\gamma}_M$ , where the ASC improvement is defined by the difference of ASC under correlated eavesdropper channels for corresponding values of correlation and the ASC under independent wiretap channels. The figure emphasizes that the ASC increases as the value of the correlation parameter increase from 0.1 to 0.8. It is because the high correlation among eavesdropper channels degrades their channel performance, which helps in improving the channel capacity of the main channel.

Figure 3.5 depicts the SOP over IID Log-normal PLC channels as a function of  $\bar{\gamma}_M$  for

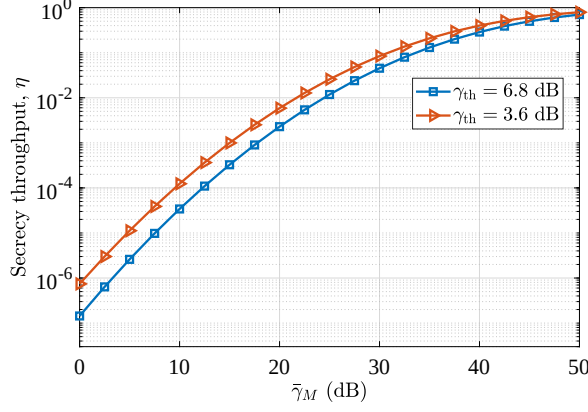


**Figure 3.7:** Secrecy throughput versus  $\bar{\gamma}_M$  for various values of  $\gamma_{th}$ .

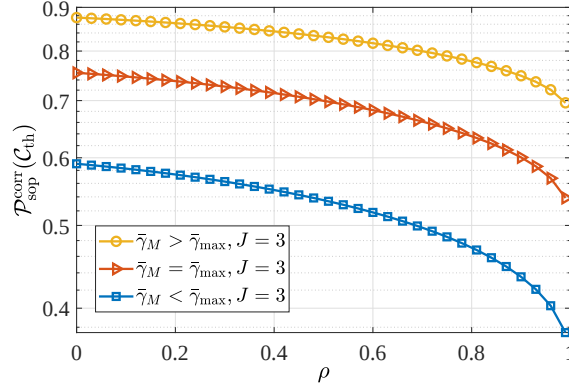


**Figure 3.8:** SOP versus  $\rho$  for different values of  $\bar{\gamma}_M$  and  $\bar{\gamma}_{max}$ .

different values of  $p$  and  $J$ , when  $K = 100$ ,  $D_M = D_{max} = 0.5$  km,  $\beta = 48$ ,  $P_L = 50$  dB/km, and  $C_{th} = 1$ . It can be observed that as the number of eavesdroppers increases, the SOP performance of the considered PLC system is degraded. Further, it can be seen from the figure that when the values of  $p$  increases from  $p = 0.05$  to  $0.4$ , the SOP performance of the considered PLC system gets poor. It is because more arrival of impulsive noise components in the PLC system increases the overall noise power of the system. As a result, there is a high probability of outage with high noise power.

Figure 3.7 depicts the secrecy throughput versus  $\bar{\gamma}_M$  for different values of  $\gamma_{th}$ , when  $p = 0.05$ ,  $C_{th} = 1$ ,  $\beta = 48$ ,  $K = 100$ , and  $\bar{\gamma}_E = 0$  dB. Herein,  $\gamma_{th} = 6.8$  dB is obtained by solving  $\mathcal{P}_{tx}(\gamma_{th}) = v$ , when  $v = 0.2$ ,  $p = 0.05$ ,  $\beta = 48$ , and the transmitted powers on the  $A$  to  $M$  link and the  $A$  to  $E$  link are fixed at 30 dB and 0 dB, respectively. Likewise,  $\gamma_{th} = 3.6$  dB is computed by assuming the condition  $\mathcal{P}_{csop}^{corr}(\gamma_{th}, \mathcal{R}_{th}) = \varrho$  for  $\varrho = 0.5$ ,  $p = 0.05$ ,  $\beta = 48$ ,  $\rho = 0.2$ , and  $J = 3$ , when the transmitted powers on the  $A$  to  $M$  link and the  $A$  to  $E$  link are fixed at 10 dB and 2 dB, respectively. It can be observed from the figure that secrecy throughput improves with a lower value of optimal  $\gamma_{th}$  because there is less chance of outage with a lower value of  $\gamma_{th}$ . Similarly, there is a high possibility of an outage with a high value of optimal  $\gamma_{th}$  due to which the secrecy throughput decreases with high value of optimal  $\gamma_{th}$ . Moreover, the computed values of optimal  $\gamma_{th}$  that maximize the secrecy throughput satisfy all the optimization conditions given in (3.65b) and (3.65c). For instance, it can be seen from the figure that when  $\gamma_{th} = 3.6$  dB, the values of  $\mathcal{P}_{csop}^{corr}(\gamma_{th}) = 0.4$  and  $\mathcal{P}_{tx}(\gamma_{th}) = 0.2$  dB when  $\gamma_{th} = 6.8$  dB, which verify the optimization conditions

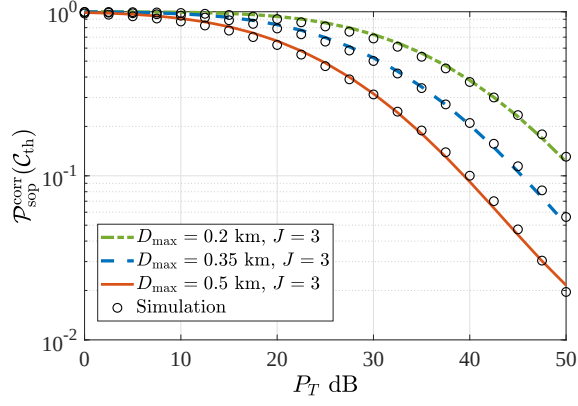


**Figure 3.9:** SOP versus  $P_T$  for different values of  $D_{\max}$ .

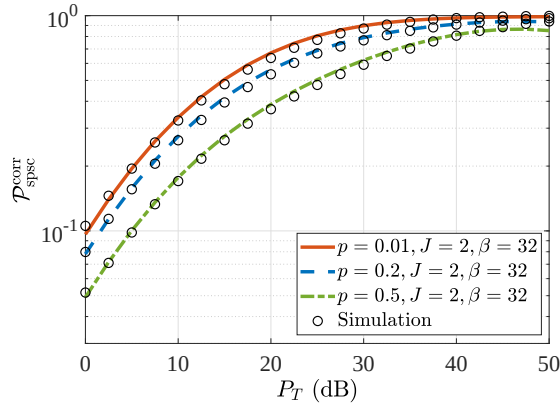


**Figure 3.10:** SPSC versus  $P_T$  for different values of  $p$ , when  $\rho = 0.1$ ,  $K = 100$ ,  $D_M = D_{\max} = 0.45$  km,  $\beta = 32$ , and  $P_L = 50$  dB/km.

in (3.65b) and (3.65c).

In Fig. 3.8, we examine the impact of the correlation parameter on SOP for different SNRs conditions ( $\bar{\gamma}_M < \bar{\gamma}_{\max}$ ,  $\bar{\gamma}_M > \bar{\gamma}_{\max}$ , and  $\bar{\gamma}_M = \bar{\gamma}_{\max}$ ), when eavesdropper channels are correlated. The curves are plotted by setting  $J = 3$ ,  $p = 0.01$ ,  $K = 100$ ,  $D_M = D_{\max} = 0.5$  km,  $\beta = 32$ ,  $P_L = 50$  dB/km, and  $C_{\text{th}} = 1$ . Further, we observed that SOP performance deteriorates highly compared to the other two conditions, when  $\bar{\gamma}_M < \bar{\gamma}_{\max}$ . It is because receiving a high SNR at the eavesdropper link increases its channel capacity. Thereby, the secrecy of the main channel reduces. In contrast, SOP performance improves, when  $\bar{\gamma}_M > \bar{\gamma}_{\max}$ . This is evident that getting higher SNR at the  $M$  increases the channel capacity of the main channel, which ultimately reduces the chance of secrecy outage. Finally, for  $\bar{\gamma}_M = \bar{\gamma}_{\max}$ , the SOP performance is moderate. Moreover, overall the SOP performance is improved with an increasing value of  $\rho$ , which shows that a higher correlation among eavesdropper channels worsens the channel. Consequently, the secrecy performance of the considered PLC system improves.

The SOP versus  $P_T$  curves for correlated eavesdropper channels for different  $D_{\max}$  is illustrated in Fig. 3.9. The curves are plotted for selected values of  $\rho = 0.1$ ,  $p = 0.01$ ,  $K = 100$ ,  $\beta = 48$ ,  $P_L = 40$  dB/km, and  $C_{\text{th}} = 1$ . It is depicted in the figure that the SOP of the considered system improves when the eavesdropper moves farther from  $A$ . It is because of the fact that when the eavesdropper distance increases from  $A$ , the SNR at the eavesdropper's link becomes poor.

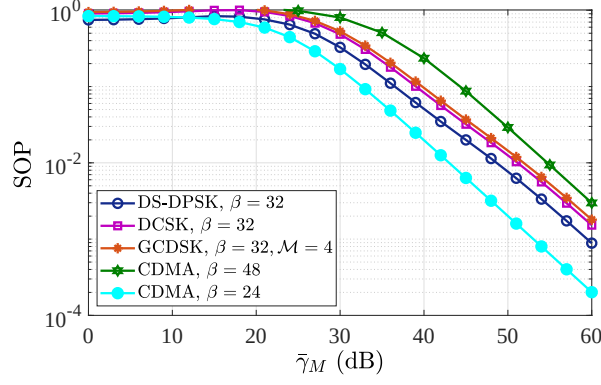


**Figure 3.11:** SOP versus  $\bar{\gamma}_M$  for different modulation schemes.

Consequently, the chance of outage is less.

In Fig. 3.10, we demonstrate the SPSC versus  $P_T$  for various values of  $p$ , when eavesdropper channels are correlated. The curves are plotted for  $\rho = 0.1$ ,  $K = 100$ ,  $D_M = D_{\max} = 0.45$  km,  $\beta = 32$ ,  $P_L = 50$  dB/km, and the transmitted power of the  $A$  to  $E$  link is fixed at 10 dB. It can be observed from the figure that the SPSC increases with  $P_T$ . Moreover, SPSC decreases with the higher impulsive noise occurrence probability from which we infer that the impulsive noise component severely affects the behavior of the considered PLC communication system.

In Fig. 3.11, we show the comparison of SOP as a function of  $\bar{\gamma}_M$  for the different modulation schemes such as DCSK, DS-DPSK, GCDSK, and CDMA. It is found that the SOP performance of DCSK is superior to GCDSK for selected values of  $\beta$  and delay block ( $\mathcal{M}$ ). Additionally, the GCDSK system structure is complex and complicated. It requires an additional delay, correlator, and multiplier [Zheng *et al.*, 2017]. However, CDMA performs worse with a higher value of  $\beta$  and vice-versa. Further, it is noticed that the SOP performance of DS-DPSK is better than DCSK. However, the DCSK system inherits chaos signal properties that make the interception and decoding of data more difficult for an eavesdropper. It is because the chaotic map uses some initial seed values to generate the chaotic carrier signal. Further, on the receiver side, to decode that chaotic signal, the receiver should know the initial seed value of the chaotic signal. If the receiver has no information about the initial seed value, it cannot decode the transmitted chaotic signal. Hence, these properties of chaos signal make the interception and decoding of data more difficult for an unknown receiver or eavesdropper.

### 3.5 Summary

In this research, we studied the secrecy performance of low-frequency PLC systems in the presence of multiple passive eavesdroppers by utilizing a DCSK modulation scheme. To this end, two different channel conditions are assumed: when all the channels are IID and when eavesdropper channels are correlated but independent of the main channel. Further, the PLS performances of the considered system were analyzed in terms of ASC, SOP, and SPSC. We also proposed an algorithm to maximize the secrecy throughput under security and reliability constraints. The algorithm is used to find the optimal SNR for which the secrecy throughput is maximum. Besides, some special cases are derived to obtain some useful insights. Through numerical results, we investigated the effects of different system parameters in order to gain a further engineering design viewpoint on the considered PLC system. The following are the key insights obtained through this chapter:

- It is found that the ASC, SOP, and SPSC performance of the considered PLC system always improve with an increasing value of the average SNR of the main channel.
- The ASC, SOP, and SPSC performance always deteriorate with the increasing number of eavesdroppers and the high occurrence of impulsive noise components in the considered PLC system.
- A high correlation among the eavesdropper channels improves the performance of both ASC and SOP. However, SOP performance improves when the eavesdropper moves farther from the Alice.
- The secrecy throughput performance is better with a lower value of optimal SNR and worse with a higher value of optimal SNR.
- Moreover, the SOP performance of the proposed system is compared to GCDSK, DS-DPSK, and CDMA. The performance of the proposed system is found to be superior to GCDSK and CDMA for specific values of  $\beta$ .

