

Pulse Jamming in PLC Over Log-Normal Channel Gain With Bernoulli-Gaussian Additive Noise

In this chapter ³, we study the impact of random pulse jamming attacks in PLC systems assuming $\mathcal{M}$ -PSK modulation technique over Log-normally distributed channel gain. The nature of PLC channel noise is described by the Bernoulli-Gaussian random process. Additionally, the state of the jammer is characterized by the Bernoulli random variable. Conditioned upon the jamming activity, we evaluate the PDF of the instantaneous SJNR and the instantaneous SNR. Capitalizing on the statistical characterization of the SJNR and SNR, we derive the series-based expressions of the ASER and OP for the considered PLC system. Further, the asymptotic ASER analysis is performed in terms of the coding gain and diversity order in the high SNR regime. In order to gain more insights into ASER and OP analysis of the considered PLC system, we demonstrate the effect of the different system parameters through the numerical results.

4.1 Introduction

PLC channels intrinsically exhibit broadcast and multipath behavior. As a consequence, PLC channels become open and shared mediums for all the end users [Cano *et al.*, 2016]. This nature of the PLC medium creates a severe challenge regarding data secrecy and privacy of an individual user in the presence of malevolent attackers such as eavesdroppers and jammers.

Jamming is an intentional act of interfering with an existing communication network to hinder legitimate communication at the physical layer by lowering the SNR at the receiver side. Due to this, data recovery becomes highly challenging at the receiving end. This action of the jammer sometimes results in conflict and denial-of-service (DoS) in the communication network [Grover *et al.*, 2014]. Generally, many types of jammers can exist in a communication network with different methods of attacks. Among them, the pulse jammer adjusts itself opportunistically between the on (active) and off (idle) state and disrupts the communication between authorized links.

Despite the fact that data integrity and confidentiality is a foremost concern for a communication technology, most of the analysis in literature related to the jamming attacks is focused on wireless communication systems [Pirayesh and Zeng, 2022], [Letafati *et al.*, 2020]. Whereas, in the field of PLC, several research studies exist in the literature regarding eavesdropping scenarios

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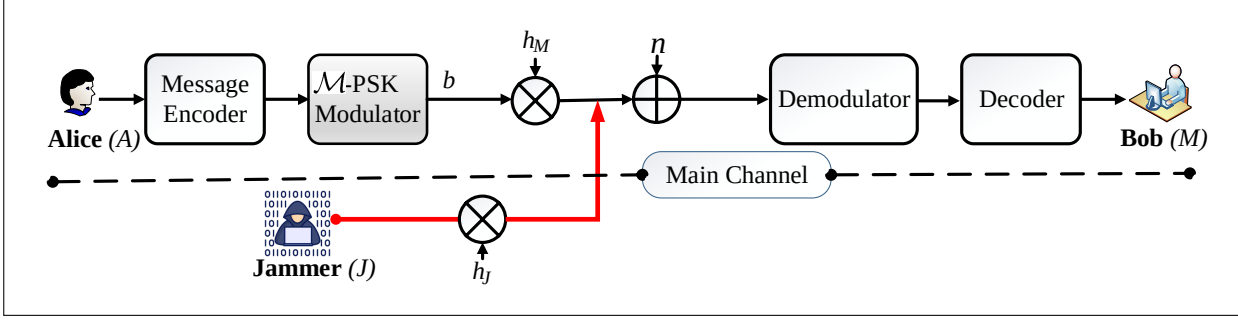


Figure 4.1: System model of the considered PLC system.

only [Pittolo and Tonello, 2014; Salem *et al.*, 2017; Zhuang and Lampe, 2014; Mohan *et al.*, 2019; Mohan and Mathur, 2022; Mohan *et al.*, 2022]. There is a lack of published research on the jamming in PLC except for [Ai *et al.*, 2017] where the authors investigated the PLC system performance in the presence of a jamming attack by employing Bayesian game theory and the Bayesian Nash equilibrium of the game was derived. To the best of the authors' knowledge, there is inadequate published research related to jamming attacks in PLC systems. Therefore, motivated by the aforementioned observations, we investigate the performance of a PLC system in the presence of pulse jamming attacks utilizing $\mathcal{M}$ -PSK modulation scheme over Log-normally distributed channel gain with additive Bernoulli-Gaussian noise.

The remainder of this chapter is organized as follows: Section 4.2 describes the considered PLC system model, where the received power, PLC channel and noise models, and the statistical characterization of the instantaneous SJNR and SNR are computed. The performance analysis of the considered PLC system is evaluated in terms of ASER, asymptotic ASER, and OP in Section 4.3. In Section 4.4, we demonstrate and discuss the numerical results. Atlast, the chapter summary is described in Section 4.5.

4.2 System Description

Let us consider a SISO PLC system model shown in Fig. 4.1, where Alice (A) sends a $\mathcal{M}$ -PSK modulated data signal to Bob (M) over the main channel in the presence of a random jammer (J). Concurrently, this jammer employs pulse jamming technique and tries to jam the legitimate communication between A and M via the main channel by strategically transmitting a signal with varying power.

4.2.1 Received Signal

The received signal at M can be expressed as

$$r = \delta_M \sqrt{P_{R_M}} h_M b + \delta_J \sqrt{N_J} h_J \mathcal{S}_J s_J + n. \quad (4.1)$$

In (4.1), b represents coherent $\mathcal{M}$ -ary PSK modulated symbol. In (4.1), $\delta_M = \exp[-(a_1 + a_2 \cdot f^y)d_M]$ and $\delta_J = \exp[-(a_3 + a_4 \cdot f^z)d_J]$ denote the attenuation factors of the PLC channel and a_1 , a_2 , a_3 , a_4 , y , and z are the attenuation parameters at a frequency f . The length of $(A - M)$ and $(J - M)$ links are indicated by d_L and d_J , respectively. Further, h_M and h_J represent the complex channel gains of the main channel and the jammer channel, respectively. Moreover, P_{R_M} is the peak received power at M and $N_J = P_J/\phi$ shows the net jammer power where P_J indicates the average jamming power and $\phi \in (0, 1]$ characterizes the probability of jamming. The PLC channel noise on the main channel is symbolized by n . Furthermore, in (4.1), s_J is the directed jamming

signal which is assumed to be unity and $\mathcal{S}_J$ describes the jamming modes (state of the jammer) which is modeled by a Bernoulli RV. Therefore, the probability distribution of $\mathcal{S}_J$ is described as [Paul *et al.*, 2019]

$$\Pr(\mathcal{S}_J = 1) = \phi, \quad \Pr(\mathcal{S}_J = 0) = 1 - \phi. \quad (4.2)$$

In (4.2), $\Pr(\mathcal{S}_J = 1) = \phi$ depicts that the jammer is in active state and during this state it sends a jamming signal over a $\mathcal{M}$ -PSK symbol interval with probability ϕ . Otherwise, it remains idle with a probability of $(1 - \phi)$ denoted by $\Pr(\mathcal{S}_J = 0)$.

4.2.2 PLC Channel Modeling

For the considered PLC system, we assume that both the main and jammer channels are Log-normally distributed. The PDF of the PLC channel gain is expressed as [Mathur *et al.*, 2018, Eq. (4)]

$$f(h_k) = \frac{1}{h_k \sqrt{2\pi\sigma_k^2}} \exp\left(-\frac{(\ln h_k - \mu_k)^2}{2\sigma_k^2}\right). \quad (4.3)$$

In (4.3), $h_k \geq 0, k \in \{M, J\}$, and μ_k and σ_k^2 are the mean and variance of the RV $\ln h_k$, respectively. Moreover, the CSI of the main and jammer channels are assumed to be known.

4.2.3 PLC Noise Modeling

PLC channels are adversely affected by a combination of background noise and impulsive noise [Kaddoum and Tadayon, 2017]. To emulate the combined effect of both these noises, Bernoulli-Gaussian random process is utilized. Hence, the total PLC additive noise can be written as [Dubey *et al.*, 2014]

$$n = \eta + P_B \cdot g. \quad (4.4)$$

In (4.4), η and g denote the Gaussian RVs corresponding to background and impulsive noise components of the Bernoulli-Gaussian PLC noise having zero mean and variances σ_η^2 and σ_g^2 , respectively. In (4.4), P_B represents Bernoulli RV with parameter p which depicts the probability of arrival of the impulsive noise component. Further, it is presumed that η , P_B , and g are independent of each other. Thus, the PDF of the PLC channel noise at the receiver M can be expressed as

$$f(n) = \sum_{i=1}^2 p_i \mathcal{N}(0, \sigma_i^2). \quad (4.5)$$

In (4.5), $\mathcal{N}(0, \sigma^2)$ indicates Gaussian distribution with zero mean and variance σ^2 , $p_1 = (1 - p)$, and $p_2 = p$. In (4.5), $\sigma_1^2 = \sigma_\eta^2$ is the background noise power and $\sigma_2^2 = \sigma_\eta^2(1 + K)$ represents the impulsive noise power, and $K = \sigma_g^2/\sigma_\eta^2$ denotes the impulsive noise index.

4.2.4 Characterization of the Instantaneous SJNR and SNR

When the jammer is in active mode, the instantaneous SJNR of the received signal at M can be expressed as

$$\gamma_{M_i}^{\text{on}} = \begin{cases} \frac{\left(\frac{\delta_M^2 |h_M|^2 P_{R_M}}{\sigma_1^2}\right)}{\left(\frac{\alpha_J^2 |h_J|^2 P_J}{\phi \sigma_1^2}\right) + 1} = \frac{\gamma_{M_1}}{\gamma_{J_1} + 1}, & \text{only background noise,} \\ \frac{\left(\frac{\delta_M^2 |h_M|^2 P_{R_M}}{\sigma_2^2}\right)}{\left(\frac{\delta_J^2 |h_J|^2 P_J}{\phi \sigma_2^2}\right) + 1} = \frac{\gamma_{M_2}}{\gamma_{J_2} + 1}, & \text{with impulsive noise.} \end{cases} \quad (4.6)$$

In (4.6), $\gamma_{M_1}=[(\delta_M^2|h_M|^2P_{R_M})/\sigma_1^2]$, $\gamma_{J_1}=[(\delta_J^2|h_J|^2P_J)/(\phi\sigma_1^2)]$, $\gamma_{M_2}=[(\delta_M^2|h_M|^2P_{R_M})/\sigma_2^2]$, and $\gamma_{J_2}=[(\delta_J^2|h_J|^2P_J)/(\phi\sigma_2^2)]$. Likewise, when the jammer is in an idle mode, then the instantaneous SNR of the received signal at M can be written as

$$\gamma_{M_i}^{\text{off}} = \begin{cases} \frac{\delta_M^2|h_M|^2P_{R_M}}{\sigma_1^2} = \gamma_{M_1}, & \text{only background noise,} \\ \frac{\delta_M^2|h_M|^2P_{R_M}}{\sigma_2^2} = \gamma_{M_2}, & \text{with impulsive noise.} \end{cases} \quad (4.7)$$

Further, the PDFs of γ_{M_i} and γ_{J_i} in (4.6) and (4.7) are obtained as follows [Mathur *et al.*, 2018, Eqs. (8-9)]:

$$f_{\gamma_{k_i}}(\gamma) = \frac{1}{\gamma_{k_i} \sqrt{2\pi\sigma_{k_i}^2}} \exp\left(-\frac{(\ln \gamma - \mu_{k_i})^2}{2\sigma_{k_i}^2}\right). \quad (4.8)$$

In (4.8), $k \in \{M, J\}$, $i \in \{1, 2\}$, $\mu_{M_1} = 2\mu_{h_M} + \ln(\delta_M^2) + \ln \bar{\gamma}_M$, and $\mu_{M_2} = 2\mu_{h_M} + \ln(\delta_M^2) + \ln \bar{\gamma}'_M$. Further, $\bar{\gamma}_M = P_{R_M}/\sigma_1^2$ denotes the average SNR when only background is present and $\bar{\gamma}'_M = \bar{\gamma}_M/(K+1)$ indicates the average SNR when impulsive noise is also present. Moreover, $\mu_{J_i} = 2\mu_{h_J} + \ln(\delta_J^2) + \ln(N_J/\sigma_i^2)$ and $\sigma_{k_i}^2 = 4\sigma_{h_k}^2$.

Now, we utilize the Gamma approximation of the Log-normal distribution as follows [Kostić, 2005, Eq. (3)]:

$$f_{\gamma_{k_i}}(\gamma) = \frac{1}{\Gamma(m_{k_i})} \left(\frac{m_{k_i}}{\omega_{k_i}}\right)^{m_{k_i}} \gamma^{m_{k_i}-1} \exp\left(-\frac{m_{k_i}\gamma}{\omega_{k_i}}\right). \quad (4.9)$$

In (4.9), $k \in \{M, J\}$, $i \in \{1, 2\}$, $m_{k_i} = 1/(\exp(\sigma_{k_i}^2) - 1)$ denotes the shaping parameter, $\omega_{k_i} = \exp(\mu_{k_i})\sqrt{(m_{k_i}+1)/m_{k_i}}$ shows the mean power, and $\Gamma(\cdot)$ is the Gamma function [Kostić, 2005].

Let us re-write $\gamma_{M_i}^{\text{on}}$ in (4.6) as $\gamma_{M_i}^{\text{on}} = (\gamma_{M_i}/\gamma_{T_i})$, where $\gamma_{T_i} = (\gamma_{J_i} + 1)$ and $i \in \{1, 2\}$. Here, $i = 1$ represents only background noise scenario and $i = 2$ indicates that both background and impulsive noises are present. Then, the CDF of $\gamma_{M_i}^{\text{on}}$ can be expressed as

$$F_{\gamma_{M_i}^{\text{on}}}(\gamma) = \Pr[(\gamma_{M_i}/\gamma_{T_i}) \leq \gamma], \gamma_{T_i} > 1. \quad (4.10)$$

Utilizing RV transformation [Papoulis and Pillai, 2002], the PDF of (4.10) is given by

$$f_{\gamma_{M_i}^{\text{on}}}(\gamma) = \int_1^\infty \gamma_{T_i} f_{\gamma_{M_i}}(\gamma\gamma_{T_i}) f_{\gamma_{T_i}}(\gamma_{T_i}) d\gamma_{T_i}. \quad (4.11)$$

Then, substituting (4.9) into (4.11), $f_{\gamma_{M_i}^{\text{on}}}(\gamma)$ can be written as

$$\begin{aligned} f_{\gamma_{M_i}^{\text{on}}}(\gamma) &= \int_1^\infty \frac{\gamma_{T_i}}{\Gamma(m_{M_i})\Gamma(m_{J_i})} \left(\frac{m_{M_i}}{\omega_{M_i}}\right)^{m_{M_i}} \left(\frac{m_{J_i}}{\omega_{J_i}}\right)^{m_{J_i}} (\gamma\gamma_{T_i})^{m_{M_i}-1} \\ &\quad \times \exp\left(-\frac{m_{M_i}\gamma\gamma_{T_i}}{\omega_{M_i}}\right) (\gamma_{T_i}-1)^{m_{J_i}-1} \exp\left(-\frac{m_{J_i}(\gamma_{T_i}-1)}{\omega_{J_i}}\right) d\gamma_{T_i}. \end{aligned} \quad (4.12)$$

Further, utilizing [Prudnikov *et al.*, 1981, Eq. (2.3.6)] into (4.12) and after some algebraic manipulations, the closed-form expression for $f_{\gamma_{M_i}^{\text{on}}}(\gamma)$ is computed as follows:

$$f_{\gamma_{M_i}^{\text{on}}}(\gamma) = \mathcal{K}_1 \gamma^{m_{M_i}-1} \exp(-\mathcal{K}_2) \Psi[m_{J_i}, \mathcal{K}_3 + 1; \mathcal{K}_2]. \quad (4.13)$$

In (4.13), $\mathcal{K}_1 = [1/\Gamma(m_{J_i})(m_{M_i}/\omega_{M_i})^{m_{M_i}}(m_{J_i}/\omega_{J_i})^{m_{J_i}} \exp(m_{J_i}/\omega_{J_i})]$, $\mathcal{K}_2 = [(m_{M_i}\gamma)/\omega_{M_i} + (m_{J_i}/\omega_{J_i})]$, $\mathcal{K}_3 = (m_{J_i} + m_{M_i})$, and $\Psi(\cdot; \cdot; \cdot)$ represents the Tricomi's (confluent Hypergeometric) function [Prudnikov *et al.*, 1981, Eq. (2.3.6)]. Likewise, the closed-form expression for $f_{\gamma_{M_i}^{\text{off}}}(\gamma)$ is written as

$$f_{\gamma_{M_i}^{\text{off}}}(\gamma) = \frac{1}{\Gamma(m_{M_i})} \left(\frac{m_{M_i}}{\omega_{M_i}}\right)^{m_{M_i}} \gamma^{m_{M_i}-1} \exp\left(-\frac{m_{M_i}\gamma}{\omega_{M_i}}\right). \quad (4.14)$$

4.3 PLC System Performance Analysis

This section presents the performance analysis of the considered PLC system by deriving the series-based expressions of ASER, asymptotic ASER, and OP.

4.3.1 ASER Performance Analysis

Let $P_\varepsilon(\gamma)$ represent the SER as a function of instantaneous SNR of the $\mathcal{M}$ -PSK system, which is given as [Proakis and Salehi, 2008, Eq. (4.3-17)]

$$P_\varepsilon(\gamma) \approx \operatorname{erfc} \left(\sqrt{\frac{\kappa\gamma}{2}} \right). \quad (4.15)$$

In (4.15), $\kappa = 2\sin^2(\pi/\mathcal{M})$ and $\operatorname{erfc}(x)$ is the complementary error function. On utilizing the Meijer's G representation of the complementary error function from [Wolfram Research, 2023b, Eq. (06.27.26.0006.01)], (4.15) is re-written as

$$P_\varepsilon(\gamma) \approx \frac{1}{\sqrt{\pi}} G_{1,2}^{2,0} \left(\frac{\kappa\gamma}{2} \middle| \begin{matrix} 1 \\ 0, 0.5 \end{matrix} \right). \quad (4.16)$$

In (4.16), $G_{p,q}^{m,n}(x|\dots)$ denotes the Meijer's G function. Hence, the total ASER of the considered PLC system can be expressed as

$$\bar{P}_{\text{SER}} = \sum_{i=1}^2 p_i \left(\phi \bar{P}_i^{\text{on}} + (1 - \phi) \bar{P}_i^{\text{off}} \right). \quad (4.17)$$

In (4.17), $\bar{P}_i^{\text{on}} = \int_0^\infty P_\varepsilon(\gamma) f_{\gamma_{M_i}}^{\text{on}}(\gamma) d\gamma$ is the ASER when the jammer is in active mode and $\bar{P}_i^{\text{off}} = \int_0^\infty P_\varepsilon(\gamma) f_{\gamma_{M_i}}^{\text{off}}(\gamma) d\gamma$ is the ASER when the jammer is in idle mode. After utilizing (4.13) and (4.16), $\bar{P}_i^{\text{on}}$ is calculated as follows:

$$\bar{P}_i^{\text{on}} = \frac{\mathcal{K}_1}{\sqrt{\pi}} \int_0^\infty \gamma^{m_{M_i}-1} \exp(-\mathcal{K}_2) \Psi[m_{J_i}, \mathcal{K}_3 + 1; \mathcal{K}_2] G_{1,2}^{2,0} \left(\frac{\kappa\gamma}{2} \middle| \begin{matrix} 1 \\ 0, 0.5 \end{matrix} \right) d\gamma. \quad (4.18)$$

Now, using [Prudnikov *et al.*, 1981, Eq. (7.11.4.1)] in (4.18), the Tricomi's function can be written in terms of the generalized Hypergeometric function (${}_pF_q(\cdot; \cdot; \cdot)$) [Prudnikov *et al.*, 1981] as

$$\begin{aligned} \bar{P}_i^{\text{on}} &= \frac{\mathcal{K}_1}{\sqrt{\pi}} \int_0^\infty \gamma^{m_{M_i}-1} \exp(-\mathcal{K}_2) [\mathcal{K}_4 {}_1F_1(m_{J_i}, \mathcal{K}_3 + 1; \mathcal{K}_2) \\ &\quad + \mathcal{K}_5 \mathcal{K}_2^{-\mathcal{K}_3} {}_1F_1(-m_{J_i}, 1 - \mathcal{K}_3; \mathcal{K}_2)] G_{1,2}^{2,0} \left(\frac{\kappa\gamma}{2} \middle| \begin{matrix} 1 \\ 0, 0.5 \end{matrix} \right) d\gamma \\ &= \mathcal{I}_{1_i} + \mathcal{I}_{2_i}. \end{aligned} \quad (4.19)$$

In (4.19), $\mathcal{K}_4 = [\Gamma(-\mathcal{K}_3)/\Gamma(-m_{J_i})]$ and $\mathcal{K}_5 = [\Gamma(\mathcal{K}_3)/\Gamma(m_{J_i})]$. Furthermore, in (4.19) using the truncated series expressions for ${}_1F_1(t; u; v) = \sum_{\varsigma=0}^\xi \frac{(t)_\varsigma v^\varsigma}{(u)_\varsigma \varsigma!}$ and $\exp(\psi) = \sum_{\lambda=0}^\Lambda \left(\frac{\psi^\lambda}{\lambda!} \right)$, $\mathcal{I}_{1_i}$ and $\mathcal{I}_{2_i}$ can be written, respectively, as

$$\begin{aligned} \mathcal{I}_{1_i} &= \frac{\mathcal{K}_1 \mathcal{K}_4}{\sqrt{\pi}} \exp \left(-\frac{m_{J_i}}{\omega_{J_i}} \right) \sum_{a=0}^A \sum_{\beta=0}^\varpi \frac{(m_{J_i})_a}{(1 + \mathcal{K}_3)_a a!} \left(\frac{\varpi}{\beta} \right) \left(\frac{m_{J_i}}{\omega_{J_i}} \right)^{\varpi-\beta} \\ &\quad \times \left(\frac{m_{M_i}}{\omega_{M_i}} \right)^\beta \int_0^\infty \gamma^{m_{M_i}+\beta-1} \exp \left(\frac{-m_{M_i}\gamma}{\omega_{M_i}} \right) G_{1,2}^{2,0} \left(\frac{\kappa\gamma}{2} \middle| \begin{matrix} 1 \\ 0, 0.5 \end{matrix} \right) d\gamma. \end{aligned} \quad (4.20)$$

$$\begin{aligned} \mathcal{I}_{2_i} = & \frac{\mathcal{K}_1 \mathcal{K}_5}{\sqrt{\pi}} \exp\left(\frac{-m_{J_i}}{\omega_{J_i}}\right) \sum_{c=0}^C \sum_{d=0}^D \frac{(-m_{M_i})_c (-1)^d}{(1 - \mathcal{K}_3)_c c!} \left(\frac{m_{M_i}}{\omega_{M_i}}\right)^{-(\mathcal{K}_3 - c - d)} \\ & \times \int_0^\infty \frac{\gamma^{m_{M_i} + d - 1}}{(\gamma + \mathcal{K}_6)^{(\mathcal{K}_3 - c)}} G_{1,2}^{2,0} \left(\frac{\kappa \gamma}{2} \middle|_{0,0.5}^1\right) d\gamma. \end{aligned} \quad (4.21)$$

In (4.21) $(W)_w = \Gamma(W + w)/\Gamma(W)$ is the Pochhammer symbol [Gradshteyn and Ryzhik, 2014], ! is the factorial operation, and $\mathcal{K}_6 = \left(\frac{m_{J_i} \omega_{M_i}}{\omega_{J_i} m_{M_i}}\right)$.

Next, with the aid of [Wolfram Research, 2023a, Eq. (07.34.21.0088.01)], [Wolfram Research, 2023a, Eq. (07.34.21.0086.01)], and after some mathematical simplification the series-based expressions for $\mathcal{I}_{1_i}$ and $\mathcal{I}_{2_i}$ can be obtained from (4.20) and (4.21), respectively, as

$$\mathcal{I}_{1_i} = \frac{\mathcal{K}_1 \mathcal{K}_4}{\sqrt{\pi}} \exp\left(-\frac{m_{J_i}}{\omega_{J_i}}\right) \left(\frac{m_{M_i}}{\omega_{M_i}}\right)^{-m_{M_i}} \sum_{a=0}^{\mathcal{A}} \sum_{\beta=0}^{\varpi} \frac{(m_{J_i})_a}{(1 + \mathcal{K}_3)_a a!} \left(\frac{\varpi}{\beta}\right) \left(\frac{m_{J_i}}{\omega_{J_i}}\right)^{\varpi - \beta} G_{2,2}^{2,1} \left(\frac{\kappa}{2} \left(\frac{\omega_{M_i}}{m_{M_i}}\right) \middle|_{0,0.5}^{1 - m_{M_i} - \beta, 1}\right). \quad (4.22)$$

$$\mathcal{I}_{2_i} = \frac{\mathcal{K}_1 \mathcal{K}_5}{\sqrt{\pi}} \exp\left(-\frac{m_{J_i}}{\omega_{J_i}}\right) \sum_{c=0}^C \sum_{d=0}^D \frac{(-m_{M_i})_c (-1)^d}{(1 - \mathcal{K}_3)_c c!} \left(\frac{m_{M_i}}{\omega_{M_i}}\right)^{-(\mathcal{K}_3 - c - d)} \frac{\mathcal{K}_6^{-m_{J_i} - c + d}}{\Gamma(\mathcal{K}_3 - c)} G_{2,3}^{3,1} \left(\frac{\kappa \mathcal{K}_6}{2} \middle|_{m_{J_i} - c - d, 0, 0.5}^{1 - m_{M_i} - d, 1}\right). \quad (4.23)$$

Remark 4.1. In (4.22) and (4.23), the infinite series converge for finite values of $\mathcal{A} = 10$, $\varpi = 10$, $C = 10$, and $D = 10$.

Next, $\bar{P}_i^{\text{off}}$ is calculated after substituting (4.14) and (4.16) as

$$\bar{P}_i^{\text{off}} = \frac{\mathcal{K}_7}{\sqrt{\pi}} \int_0^\infty \gamma^{m_{M_i} - 1} \exp\left(\frac{-m_{M_i} \gamma}{\omega_{M_i}}\right) G_{1,2}^{2,0} \left(\frac{\kappa \gamma}{2} \middle|_{0,0.5}^1\right) d\gamma. \quad (4.24)$$

In (4.24), $\mathcal{K}_7 = [1/\Gamma(m_{M_i})(m_{M_i}/\omega_{M_i})^{m_{M_i}}]$.

Similarly, utilizing [Wolfram Research, 2023a, Eq. (07.34.21.0088.01)] and after some mathematical simplifications in (4.24), the series-based expression for $\bar{P}_i^{\text{off}}$ can be derived as

$$\bar{P}_i^{\text{off}} = \frac{1}{\sqrt{\pi} \Gamma(m_{M_i})} G_{2,2}^{2,1} \left(\frac{\kappa}{2} \left(\frac{\omega_{M_i}}{m_{M_i}}\right) \middle|_{0,0.5}^{1 - m_{M_i}, 1}\right). \quad (4.25)$$

Finally, substituting (4.22), (4.23), and (4.25) into (4.17), we obtain the overall series-based expression for the total ASER of the considered PLC system.

Remark 4.2. In order to analyze the effect of P_J , from (4.17), it is observed that as the value of P_J increases, μ_{J_i} and ω_{J_i} increase. As a result, the ratio $\left(\frac{m_{J_i}}{\omega_{J_i}}\right)$ in (4.22) decreases and $\mathcal{I}_{1_i}$ reduces. Concurrently, as P_J increases $\mathcal{K}_6$ in (4.23) decreases and the overall value of Meijer's G function and $\mathcal{K}_6^{-(m_{J_i} + c - d)}$ rapidly increase. Owing to this, $\mathcal{I}_{2_i}$ becomes more dominant in $\bar{P}_i^{\text{on}}$ whereas $\bar{P}_i^{\text{off}}$ remains constant. Hence, $\bar{P}_i^{\text{on}}$ increases and as a result, the ASER of the considered system increases. This analysis is also justified from Fig. 4.2 in Section 4.4. A similar theoretical analysis can be conducted to analyze the trend of the other parameters on the ASER performance.

4.3.2 Asymptotic ASER Analysis

In order to comprehensively investigate the ASER analysis, we present the asymptotic analysis of the ASER in terms of coding gain and diversity order under high values of average SNR.

To do so, let us carefully observe (4.19) and (4.24). As $\bar{\gamma}_M \rightarrow \infty$, the generalized Hypergeometric function and $\mathcal{K}_2$ in (4.19) tend to unity, i.e., ${}_1F_1(\cdot, \cdot; \cdot) \rightarrow 1$ and $\mathcal{K}_2 \rightarrow 1$. Similarly, as $\bar{\gamma}_M \rightarrow \infty$, the term $\exp\left(\frac{-m_{M_i}\gamma}{\omega_{M_i}}\right)$ in (4.24) becomes unity. Finally, the total ASER of the considered PLC system can be approximated as follows:

$$\lim_{\bar{\gamma}_M \rightarrow \infty} \bar{P}_{\text{SER}} = \sum_{i=1}^2 p_i \mathcal{G}_c \left(\frac{1}{\omega_{M_i}(\bar{\gamma}_M)} \right)^{\mathcal{D}_o}. \quad (4.26)$$

In (4.26) $\mathcal{G}_c = [\phi \mathcal{G}_{c_i}^{\text{on}} + (1 - \phi) \mathcal{G}_{c_i}^{\text{off}}]$ represents the coding gain and $\mathcal{D}_o = m_{M_i}$ is diversity order. In (4.26), $\mathcal{G}_{c_i}^{\text{on}} = \mathcal{K}_8 \int_0^\infty \gamma^{m_{M_i}-1} \text{erfc}[\sqrt{(\kappa\gamma)/2}] d\gamma$ and $\mathcal{G}_{c_i}^{\text{off}} = \mathcal{K}_9 \int_0^\infty \gamma^{m_{M_i}-1} \text{erfc}[\sqrt{(\kappa\gamma)/2}] d\gamma$ where $\mathcal{K}_8 = (m_{M_i})^{m_{M_i}} / \Gamma(m_{M_i}) (m_{J_i}/\omega_{J_i})^{m_{J_i}} (\mathcal{K}_4 + \mathcal{K}_5 (m_{J_i}/\omega_{J_i})^{-\mathcal{K}_3})$, and $\mathcal{K}_9 = \left[\frac{(m_{M_i})^{m_{M_i}}}{\Gamma(m_{M_i})} \right]$. Further, approximating $\text{erfc}[\sqrt{(\kappa\gamma)/2}] \leq \exp(-(\kappa\gamma)/2)$ and utilizing [Gradshteyn and Ryzhik, 2014, Eq. (3.478.1)] in $\mathcal{G}_{c_i}^{\text{on}}$ and $\mathcal{G}_{c_i}^{\text{off}}$, their closed-form expressions are evaluated as

$$\mathcal{G}_{c_i}^{\text{on}} = \mathcal{K}_8 (\kappa/2)^{m_{M_i}} \Gamma(m_{M_i}), \quad (4.27)$$

$$\mathcal{G}_{c_i}^{\text{off}} = \mathcal{K}_9 (\kappa/2)^{m_{M_i}} \Gamma(m_{M_i}). \quad (4.28)$$

Finally, substituting (4.27) and (4.28) into (4.26), the closed-form expression of the asymptotic ASER can be obtained as follows:

$$\lim_{\bar{\gamma}_M \rightarrow \infty} \bar{P}_{\text{SER}} = \sum_{i=1}^2 p_i [\phi \mathcal{K}_8 + (1 - \phi) \mathcal{K}_9] (\kappa/2)^{m_{M_i}} \Gamma(m_{M_i}) \left(\frac{1}{\omega_{M_i}(\bar{\gamma}_M)} \right)^{\mathcal{D}_o}. \quad (4.29)$$

Remark 4.3. The diversity order of the considered PLC system under the pulse jamming attack depends only on the shaping parameter (m_{M_i}) of the main channel and is independent of the shaping parameter of the jammer channel, whereas the coding gain depends on both the shaping parameters.

4.3.3 OP Analysis

When the jammer is in active mode, the OP of the considered PLC system can be formulated as

$$P_{\text{out}} = \sum_{i=1}^2 p_i \left(\phi P_{\text{out}_i}^{\text{on}} + (1 - \phi) P_{\text{out}_i}^{\text{off}} \right). \quad (4.30)$$

In (4.30), $P_{\text{out}_i}^{\text{on}} = \int_1^\infty \int_{-\infty}^{\gamma_{T_i} \gamma_{\text{th}}} f_{\gamma_{M_i}}(\gamma_{M_i}) f_{\gamma_{T_i}}(\gamma_{T_i}) d\gamma_{M_i} d\gamma_{T_i}$ and $P_{\text{out}_i}^{\text{off}} = \int_0^{\gamma_{\text{th}}} f_{\gamma_{M_i}}(\gamma_{M_i}) d\gamma_{M_i}$. Here, γ_{th} is the threshold SNR.

Further, substituting (4.9) into $P_{\text{out}_i}^{\text{on}}$ and $P_{\text{out}_i}^{\text{off}}$ and utilizing [Prudnikov *et al.*, 1981, Eq. (2.3.6)] and [Gradshteyn and Ryzhik, 2014, Eq. (3.381.1)], respectively, the series based expression and the closed-form expression for $P_{\text{out}_i}^{\text{on}}$ and $P_{\text{out}_i}^{\text{off}}$ are obtained, respectively, as

$$P_{\text{out}_i}^{\text{on}} = \mathcal{K}_{10} \sum_{\ell=0}^L \frac{1}{\Gamma(\ell+1)} \left(\frac{m_{M_i} \gamma_{\text{th}}}{\omega_{M_i}} \right)^\ell \exp(-\mathcal{K}_{11}) \Psi[m_{J_i}, \mathcal{K}_3 + \ell + 1; \mathcal{K}_{11}], \quad (4.31)$$

$$P_{\text{out}_i}^{\text{off}} = 1 - 1/\Gamma(m_{M_i}) \Upsilon[m_{M_i}, (m_{M_i} \gamma_{\text{th}}/\omega_{M_i})]. \quad (4.32)$$

In (4.32), $\iota = (m_{M_i} + \ell)$, $\Upsilon(\cdot, \cdot)$ is the lower incomplete Gamma function [Gradshteyn and Ryzhik, 2014, Eq. (3.381.1)], $\mathcal{K}_{10} = [(\omega_{J_i}/m_{J_i})^{m_{J_i}} \exp(m_{M_i}/\omega_{M_i})]$, and $\mathcal{K}_{11} = [(m_{M_i}/\omega_{M_i}) + ((m_{M_i} \gamma_{\text{th}})/\omega_{M_i})]$.

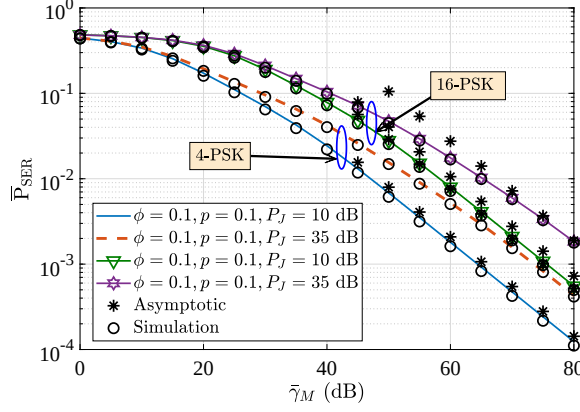


Figure 4.2: ASER as a function of $\bar{\gamma}_M$ for various values M and P_J .

In (4.31), the infinite series converges for finite value of $L = 10$. Finally, substituting (4.31) and (4.32) into (4.30), the series-based expression of the OP for the considered PLC system can be obtained as

$$P_{\text{out}} = \sum_{i=1}^2 p_i \left[\phi \left(\mathcal{K}_{10} \sum_{\ell=0}^L \frac{1}{\Gamma(\ell+1)} \left(\frac{m_{M_i} \gamma_{\text{th}}}{\omega_{M_i}} \right)^\ell \exp(-\mathcal{K}_{11}) \Psi[m_{J_i}, \mathcal{K}_3 + \ell + 1; \mathcal{K}_{11}] \right) + (1 - \phi) \left(1 - \frac{1}{\Gamma(m_{M_i})} \Upsilon \left[m_{M_i}, \frac{m_{M_i} \gamma_{\text{th}}}{\omega_{M_i}} \right] \right) \right]. \quad (4.33)$$

Remark 4.4. From (4.31)-(4.33), where any non-zero value of ϕ indicates the presence of jammer, it is observed that as ϕ increases, the ratio (ω_{J_i}/m_{J_i}) increases due to P_J . As a result, the factor $\mathcal{K}_{10}$ and $P_{\text{out}_i}^{\text{on}}$ increase. Concurrently, $P_{\text{out}_i}^{\text{off}}$ which is independent of P_J , starts decreasing by a factor $(1 - \phi)$. Consequently, $P_{\text{out}_i}^{\text{on}}$ and P_{out} increase. Hence, the OP of the considered PLC system increases with ϕ . This analysis is also verified from Fig. 4.4 in Section 4.4. A similar theoretical analysis can be conducted to analyze the trend of the other parameters on the OP performance.

4.4 Numerical Results and Discussion

In this section, numerical results are discussed to demonstrate the performance of the considered PLC system based on the derived analytical expressions in the previous section. The parameter values used for obtaining the results are [Zimmermann and Dostert, 2002b]: $f = 1$ MHz, $d_M = 200$ m, $d_J = 300$ m, $a_1 = 9.33 \times 10^{-3}$ m $^{-1}$, $a_2 = 3.24 \times 10^{-7}$ s/m, $a_3 = 8.40 \times 10^{-3}$ m $^{-1}$, $a_4 = 3 \times 10^{-9}$ s/m, $y = 0.7$, and $z = 1$.

Figure 4.2 illustrates the ASER as a function of $\bar{\gamma}_M$ for different values of M and P_J when $\phi = 0.1$, $p = 0.1$, and $K = 100$. It can be seen from the figure that the ASER performance improves as the values of $\bar{\gamma}_M$ increase. It is also worth noting that the ASER performance degrades with the increasing values of $M = 4$ to 16. Further, the ASER performance also reduces with increasing value of P_J . Additionally, the asymptotic ASER curves versus $\bar{\gamma}_M$ are also depicted in Fig. 4.2. For instance for 4-PSK, the ASER is 4.2×10^{-4} and 1.1×10^{-4} at 70 dB and 80 dB, respectively, for $p = 0.1, \phi = 0.1, K = 100$, and $P_J = 10$ dB. Hence, the asymptotic slope is computed as $\log_{10}(4.2 \times 10^{-4}) - \log_{10}(1.1 \times 10^{-4}) = 0.5819 \approx m_{M_i}$, which verifies the diversity order derived in Section 4.3.2. From the system design aspect, the average SNR of the main channel is an important parameter to improve the ASER performance of the considered PLC system under the pulse jamming attacks.

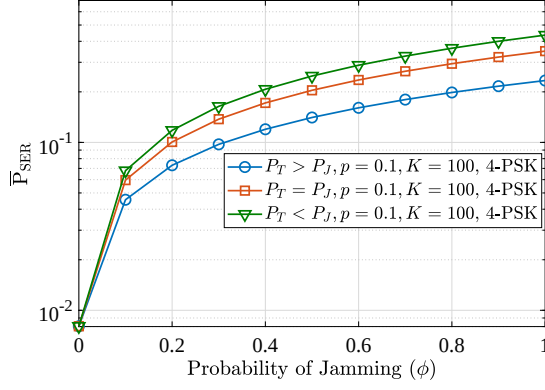


Figure 4.3: ASER versus ϕ for different values of P_T and P_J .

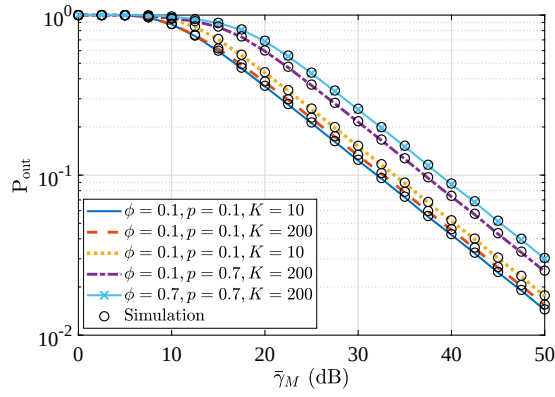


Figure 4.4: OP versus $\bar{\gamma}_M$ for $P_J = 3$ dB, $\gamma_{th} = 5$ dB, and different values of p , K , and ϕ .

In Fig. 4.3, we plot the ASER for 4-PSK versus ϕ for different transmitted power conditions ($P_T > P_J$, $P_T = P_J$, and $P_T < P_J$) when $p = 0.1$, and $K = 100$. It can be inferred from the figure that when $P_T > P_J$, the ASER performance is better compared to the other two conditions. This is because transmitting greater power than the jammer increases the overall SJNR of the main channel, as a consequence, the overall ASER performance improves. Similarly, when $P_T < P_J$, the ASER performance becomes poor. This implies that injecting higher power signal by the jammer decreases the overall SJNR of the main channel, consequently, the ASER performance deteriorates. Moreover, for $P_T = P_J$, the ASER performance remains moderate. Finally, from the plots, it is concluded that the overall ASER performance of the considered PLC system always decreases when the probability of jamming increases. This analysis provides an important system design insight that allocating an optimal transmitted power for the main channel helps in providing resistance against the pulse jamming attacks.

Figure 4.4 presents OP versus $\bar{\gamma}_M$ curves for $P_J = 3$ dB, $\gamma_{th} = 5$ dB, and different values of p , K , and ϕ . From the plots, it is inferred that the OP performance worsens when the values of p and K increase. It is because higher values of p indicate higher occurrence of the impulsive noise components into the PLC channel. As a result, the OP performance of the considered PLC system degrades. Similarly, higher values of K show higher ratio of impulsive noise to background noise. As a consequence, as the impulsive noise power increases, the overall OP performance of the proposed system deteriorates. Similarly, the OP performance of the considered PLC system also deteriorates when ϕ increases from 0.1 to 0.7. From the system design viewpoint, the average SNR of the main channel is a significant parameter to improve the OP performance of the considered

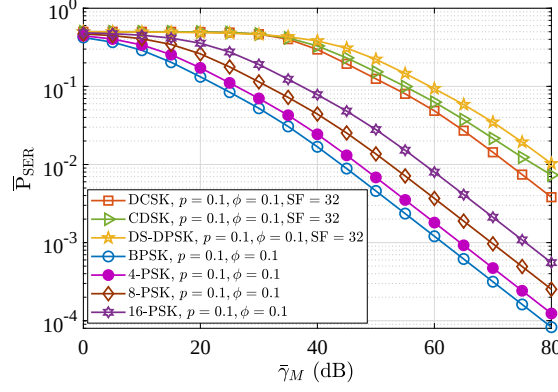


Figure 4.5: Comparison of ASER versus $\bar{\gamma}_M$ for different modulation schemes.

PLC system against the pulse jamming attacks. Furthermore, this analysis reveals that during system design, efforts must be made to minimize the impact of impulsive noise, through filtering, blanking-clipping, and iterative based error control coding methods [Shongwey *et al.*, 2014].

Figure 4.5 demonstrates the comparison of ASER versus $\bar{\gamma}_M$ for various modulation schemes, such as $\mathcal{M}$ -PSK, DCSK, CDSK, and DS-DPSK when $p = 0.1, \phi = 0.1$, spreading factor (SF) = 32, and P_J is 10 dB. It is observed that the ASER performance of $\mathcal{M}$ -PSK is better than DCSK, CDSK, and DS-DPSK for certain values of $\mathcal{M}$. Thus, for the proposed PLC system, our results indicate that $\mathcal{M}$ -PSK modulation is more robust towards jamming attacks compared to DCSK, CDSK, and DS-DPSK.

4.5 Summary

This chapter analyzed the ASER and OP performance of a PLC system under random pulse jamming attacks employing $\mathcal{M}$ -PSK modulation technique. We observed the impacts of various system parameters via numerical outcomes to gain additional engineering design insight into the proposed PLC system. The key insights obtained from this chapter comprise the following:

- The ASER and OP performance increase with an increasing value of the average SNR of the main channel.
- This study demonstrates that the ASER and OP performance of the considered PLC system worsen with a higher jamming power, higher probability of jamming, and impulsive noise components.
- The asymptotic study reveals that the diversity order of the considered PLC system under the pulse jamming attack depends only on the shaping parameter of the main channel and is independent of the shaping parameter of the jammer channel, whereas the coding gain depends on both the shaping parameters.
- The proposed $\mathcal{M}$ -PSK modulation-based PLC system outperforms the DCSK, CDSK, and DS-DPSK modulation schemes.