Security performance analysis of SIMO relay systems over Composite Fading Channels

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Abstract

In this paper, we analyze the secrecy performance of single-input multiple-output (SIMO) relay systems over κ-μ shadowed fading channels. Based on considering relay model employing decode-and-forward (DF) protocol, two security evaluation metrics, namely, secure outage probability (SOP) and probability of strictly positive secrecy capacity (SPSC) are studied, for which closed-form analytical expressions are derived. In addition, Monte Carlo results prove the validity of the theoretical derivation. The simulation results confirm that the factors that enhance the security include large ratio of (μ_D, μ_E), (m_D, m_E), (L_D, L_E) and small ratio of (k_D, k_E) under the high signal-to-noise ratio regime.

Keywords: Cooperative relay, composite fading, performance analysis, physical layer security, decode-and-forward

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1. Introduction

Different from traditional approaches of solving the security problem of wireless communication, physical layer security (PLS) focuses on utilizing the characteristics of the transmission channels, rather than relying on the high complexity encryption/decryption system [1]. In recent years, the research on PLS has made a gratifying progress [2-8]. Wang *et al.* in [2] developed a integration framework to improve the PLS performance of internet of things (IOT) networks. Moreover, the IOT networks requires that heterogeneous terminals can communicate directly, so cross-technology communications (CTC) technology emerges as the times require [3]. The authors of [4] studied the security performance of CTC communication by using the inherent characteristics of physical layer. In [5], the derivations of SOP and PNSC of cognitive radio networks over Nakagami-*m* fading channels were obtained. Lei *et al.* provided security performance analysis for different generalized fading channels including generalized Gamma [6] and α-μ fading [7]. To investigate the security performance of free space optical (FSO) networks, the lower bound of SOP and SPSC over mixed model composed of Rayleigh and generalized-*K* fading channels were given in [8].

As a promising technology to overcome the adverse effects of signal attenuation in the wireless communication networks (WCNs), relaying schemes that can significantly improve the transmission range and quality have gained great attention in recent literature [9-17]. Chen *et al.* in [9] studied confidentiality of a cooperative relay network over Rayleigh fading channels by deducing SOP in two scenarios, namely, full duplex and half duplex. In [10], the security analysis of satellite communication systems over Rayleigh fading channels with multiple eavesdroppers was investigated. The authors of [11] studied the security performance of single-antenna relay systems over generalized-*K* fading channels, where the SOP, probability of strictly positive secrecy capacity (SPSC) and ASC were presented based on amplify-and-forward (AF) protocol. In [12], Peppas *et al.* considered a composite channel model in which the link from the source to the relay node undergoes η-μ fading and the channel from the relay to the target node is subject to κ-μ fading, In particular, closed-form expressions for the OP and average bit error probability (ABEP) were given for analysis. On the premise of fully considering the unfavorable factors in communication networks, the exact and approximate OP for relaying systems over Weibull distribution were presented in [13]. The authors in [14] proposed a relay system in which the relay node was based on AF with multiple antennas. According to this model, ASC was derived to analyze the security performance. In [15], a decode-and-forward (DF) relay model was provided, and OP and IP were derived over Nakagami-*m* fading channels. The performance of the relaying non-orthogonal multiple access (NOMA) networks over Rayleigh fading and α-μ fading were analyzed in [16] and [17], respectively.

It is worth mentioning that the use of multi-antenna is an important measure to improve the channel capacity of WCNs and is applied to practical scenarios such as mobile phone communication [18], radar networks [19], vehicle-to-vehicle systems [20], etc. Recently, many scholars have investigated the enhancement of PLS with the aid of multi-antenna technologies. Zhou *et al.* in [21] analyzed the security performance for the Wyner's model with multiple antennas over *K* fading channels, elaborated the derivation of ASC, SOP and SPSC, and verified them by Monte Carlo simulations. The authors of [22] proposed a multi-antenna composite relaying system, where the channel from the signal source to the relay and to the eavesdropping user experiences Nakagami-*m* fading, while the link from the relay to the legitimate receiver undergoes generalized-*K* fading, Moreover, the closed-form OP and IP were derived for secrecy analysis. The study [23] presented a simultaneous wireless information and power transfer (SWIPT) system over Rayleigh fading channels with multi-antenna receivers, and theoretical SOP and ASC were obtained. The confidentiality of SIMO system over generalized-*K* fading channels was analyzed in [24]. In [25], the PLS of the smart city model over two Nakagami-*m* fading was studied, where the transmitter is equipped with multiple antennas, and the influence of the number of antennas on the system security was discussed. By approximating the probability density function (PDF) of α-μ distribution to bivariate Fox's H-function, the authors of [26] deduced and analyzed the SOP of multi-antenna network under consideration, and presented the influences of shape parameters (α and μ) on the secrecy performance.

In recent years, the related work mainly involves the researches of statistical characteristics, physical layer performance and security performance on the κ-μ shadowed fading channels. The κ-μ shadowed distribution is a composite model, which considers both multipath fading and shadow fading simultaneously, and can simulate the environments of inhomogeneous scattering, for instance, IoT networks [27], double-hop satellite communication [28], and fifth generation (5G) transmission [29]. The author in [30] proposed the κ-μ shadowed model and presented its statistical characteristics including PDF, cumulative distribution function (CDF) and moment generating function (MGF). Aiming to reduce the complexity of integral calculations, a concise formula on bit error rate (BER) was given based on the approximation of *Q* function [31]. To analyze the performance of mult-hop networks experiencing κ-μ shadowed fading channels, the ABEP based on optimum relay positioning (ORP) and optimum power allocation (OPA) protocols were derived by the MGF in [32]. In [33], the authors studied the performance analysis of the WCNs with double hop AF relay over the κ-μ shadowed fading channels. Srinivasan *et al.* in [34] studied the secrecy performance of Wyner's eavesdropping networks over the κ-μ shadowed fading channels, and obtained the approximate SOP and SPSC. Relying on the proposed cognitive radio network (CRN) model, the authors of [35] provided the moment matching expression for PDF on κ-μ shadowed distribution, and derived the exact and approximate OP to analyze the influence of parameters on system performance. To explore the performance of AF relaying systems undergoing κ-μ shadowed fading, the precise and approximate OP and average capacity were provided in [36]. Sun. *et al.* in [37] studied the secrecy performance of single-input single-output (SISO) networks over the κ-μ shadowed fading channels, and obtained the approximate SOP and SPSC. As a progressive study of [37], the confidentiality for correlated SIMO κ-μ shadowed channel were investigated in [38]. To explore the PLS of AF relaying systems undergoing κ-μ shadowed fading, the precise and approximate OP and average capacity were provided in [39]. The OP of CRNs considering DF multiple relays over κ-μ shadowed fading was obtained by Nakagami-*m* approximation in [40].

According to the best of the authors' knowledge, there has been no published literatures involving the PLS of relaying κ-μ shadowed systems, let alone the multi-antenna scenarios. Motivated by exploring the PLS performance of communication scenarios that can be simulated with relaying networks over κ-μ shadowed fading channels, in this paper, we first present a realistic relay eavesdropping model with multiple antennas. After that, based on the DF relay protocol, we derive closed-form analytical formulas of two important scerecy performance benchmarks, namely SOP and SPSC. Finally, we provide a comparison between the numerical results of statistical and theoretical simulation, and discuss the factors that affect the confidentiality of the proposed system.

The subsequent contents are arranged as follows. Section 2 provides a mathematical model of the relay system under consideration and an overview of κ-μ shadowed fading distribution. In section 3, we derive the closed-form representations of SOP regarding the DF relay eavesdropping model. The theoretical SPSC is given in section 4. The numerical results and some discussions on improving the secrecy performance are presented in section 5. Section 6 concludes the paper and outlines the main findings of this work.

2. System Model and Channel Characteristics

2.1 System Model

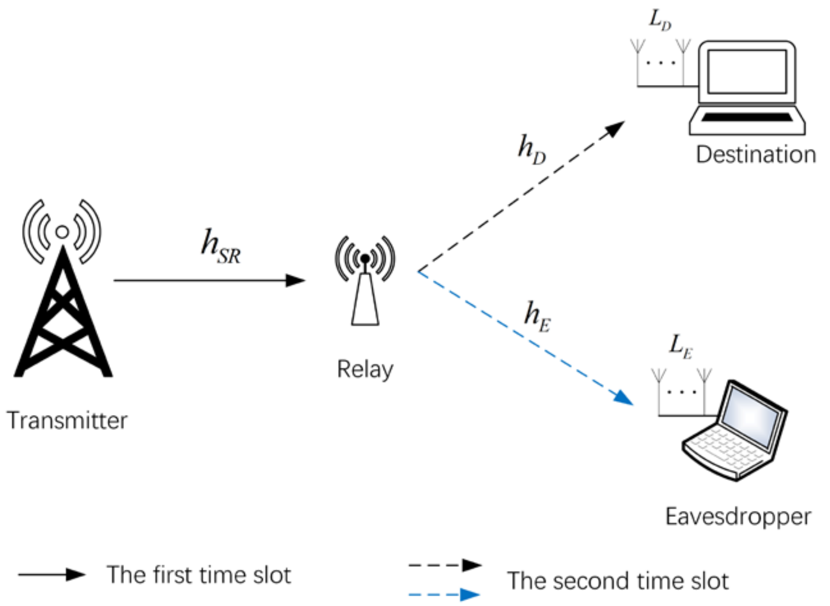

Fig. 1. The system model of the considered scenario

The considered system model with four-nodes is depicted in **Fig. 1**, where the transmitter (S) is responsible for sending confidential signals, the relay (R) decodes and forwards the signals, the destination (D) represents the expected receiver, while the eavesdropper (E) attempts to intercept confidential information. D and E are equipped with multiple antennas, and the combination method is maximum ratio combining (MRC), while S and R are single antenna nodes, and all links ($S \to R$, $R \to D$, $R \to E$) experience independent and identically distributed κ-μ shadowed fading. We assume that the relay is based on DF protocol, and the relay node (R) master the channel state information (CSI) of main link, but has no information about the eavesdropping link. It should be noted that due to severe fading, there are no direct connection on links of $S \to D$, $S \to E$ [41] [42]. the system model can be can be used to evaluate the PLS performance of SIMO WCNs (device-to-device communication, 5G, etc.) with relay nodes.

The communication in the considered relay network consists of signal transmission in two time slots. At the first time slot, a confidential message x is sent by S to R, and the message received by R is written as

$$y_R = \sqrt{P_S} h_{SR} x + z_{SR}, \tag{1}$$

where h_{SR} is the complex channel gain between *S* and *R*, and z_{SR} denotes additive white Gaussian noise (AWGN) with zero mean and variance σ_{SR}^2, P_S is the transmission power of the signal source.

In the second time slot, employing DF relay which means that the signal will be forwarded by the relay node only after the decoding is successful. In the system model, *R* transmits secrecy signal to *D* and *E* through the legitimate channel ($R \to D$) and eavesdropping channel ($R \to E$), respectively. We can express the message received at *D* or *E* as

$$\mathbf{y}_{Ri} = \sqrt{P_R}\mathbf{h}_{Ri}y_R + \mathbf{z}_{Ri}, \quad i \in \{D, E\}, \tag{2}$$

where the value of *i* indicates the legitimate link (*i* = *D*) or eavesdropping link (*i* = *E*), $\mathbf{y}$, $\mathbf{h}$ and $\mathbf{z}$ are three vectors representing the received signal, channel gain and complex AWGN. P_R denotes the transmitted power at the relay node.

On the basis of (1) and (2) and [15], we can obtain the end-to-end signal-to-noise ratio (SNRs) as

$$\gamma_{SD} = \sum_{j=1}^{L_D}\gamma_{SD_j} = \min\left\{L_D\gamma_{SR}, \sum_{j=1}^{L_D}\gamma_{RD_j}\right\} = \min\{L_D\gamma_{SR}, \gamma_D\}, \tag{3}$$

$$\gamma_{SE} = \sum_{j=1}^{L_E}\gamma_{SE_j} = \min\left\{L_E\gamma_{SR}, \sum_{j=1}^{L_E}\gamma_{RE_j}\right\} = \min\{L_E\gamma_{SR}, \gamma_E\}, \tag{4}$$

where γ is the end-to-end SNR, L_D and L_E are the number of receiving antennas at *D* and *E*.

2.2 Channel Characteristics

In this subsection, we describe the statistical characteristics of κ-μ shadowed distribution. In the system model considered, the channel of $S \to R$ is a SISO link. According [30] and [43, Eq. (9.210.1)], the PDF for SNR at *R* can be written as

$$f_{SR}(\gamma) = a_{SR}{}^{\mu_{SR}} b_{SR}{}^{-m_{SR}} \frac{1}{\Gamma(\mu_{SR})} \sum_{q_3=0}^{\infty} \frac{(m_{SR})_{q_3}}{(\mu_{SR})_{q_3} q_3!} \left(\frac{a_{SR}k_{SR}\mu_{SR}}{b_{SR}m_{SR}}\right)^{q_3} \gamma^{\mu_{SR}+q_3-1} \exp(-a_{SR}\gamma), \tag{5}$$

where $a_i = \mu_i(1+k_i)/\Omega_i$, $b_i = \mu_i k_i + m_i / m_i$, k_i, μ_i, and m_i are the shape parameters for κ-μ shadowed fading channels. Ω_i means the average SNRs for each channels. $\Gamma(\cdot)$ is defined as the Gamma function [43, Eq. (8.310.1)], and $(x)_q$ denotes pochammer operation [43].

For the channels $R \to D$ and $R \to E$, there are multiple fading subchannels due to multiantennas reception, and the PDF for the received SNR at *D* or *E* can be stated as [44]

$$f_i(\gamma) = (L_i a_i)^{L_i\mu_i} (b_i)^{-Lm_i} \frac{1}{\Gamma(L_i\mu_i)} \times \sum_{q=0}^{\infty} \frac{(L_i m_i)_q}{(L_i\mu_i)_q q!} \left(\frac{L_i a_i k_i \mu_i}{b_i m_i}\right)^q \gamma^{L_i\mu_i+q-1} \exp(-L_i a_i \gamma), \ i \in \{D, E\}. \tag{6}$$

3. SOP Analysis

As an important metric to evaluate the security capability of WCNs, SOP can be interpreted as the probability that the instantaneous secrecy rate is lower than a predetermined threshold value C_{th} [45]. From [6], we can obtain SOP as

$$SOP = P\{C_S \le C_{th}\} = P\{C_{SD} - C_{SE} \le C_{th}\} = 1 - P\{C_S > C_{th}\}, \tag{7}$$

where $C_S = \max\{\ln(1+\gamma_{SD}) - \ln(1+\gamma_{SE}), 0\}$, $C_{SD} = \ln(1+\gamma_{SD})$ and $C_{SE} = \ln(1+\gamma_{SE})$ are the instantaneous capacity of legitimate channel and eavesdropping channel, respectively. Combined with (3), (4) and (7), we can divide the calculation of $P\{C_S > C_{th}\}$ into four cases as

$$\begin{aligned} P\{C_S > C_{th}\} &= P\{C_{SD} - C_{SE} > C_{th}\} \\ &= P\{1 + \min(L_D\gamma_{SR}, \gamma_D) > \Theta(1 + \min(L_E\gamma_{SR}, \gamma_E))\} \\ &= \Phi_1 + \Phi_2 + \Phi_3 + \Phi_4, \end{aligned} \tag{8}$$

where $\Theta = \exp(C_{th}) \ge 1$, and

$$\Phi_1 = P\{1+\gamma_D > \Theta(1+\gamma_E), L_D\gamma_{SR} > \gamma_D, L_E\gamma_{SR} > \gamma_E\}, \tag{9}$$

$$\Phi_2 = P\{1+\gamma_D > \Theta(1+L_E\gamma_{SR}), L_D\gamma_{SR} > \gamma_D, L_E\gamma_{SR} < \gamma_E\}, \tag{10}$$

$$\Phi_3 = P\{1+L_D\gamma_{SR} > \Theta(1+\gamma_E), L_D\gamma_{SR} < \gamma_D, L_E\gamma_{SR} > \gamma_E\}, \tag{11}$$

$$\Phi_4 = P\{1+L_D\gamma_{SR} > \Theta(1+L_E\gamma_{SR}), L_D\gamma_{SR} < \gamma_D, L_E\gamma_{SR} < \gamma_E\}. \tag{12}$$

Obviously, referring to (9), (10), (11) and (12), when $L_D \le L_E$, Φ_2 and Φ_4 are impossible to occur, hence, we have $\Phi_2 = \Phi_4 = 0$, and $P\{C_S > C_{th}\}$ can then be simplified as

$$P\{C_S > C_{th}\} = \Phi_1 + \Phi_3. \tag{13}$$

However, for $L_D > L_E$, all four cases are possible, and the probability can be written as

$$P\{C_S > C_{th}\} = \Phi_1 + \Phi_2 + \Phi_3 + \Phi_4. \tag{14}$$

Utilizing (5) and (6), we can derive Φ_1 as

$$\begin{aligned} \Phi_1 &= P\{\Theta(1+\gamma_E) - 1 < \gamma_D < L_D\gamma_{SR}, L_E\gamma_{SR} > \gamma_E\} \\ &= \int_0^\infty f_{\gamma_{SR}}(x) \int_0^{L_E x} f_E(y) \int_{\Theta(1+y)-1}^{L_D x} f_D(z)\, dz dy dx \\ &= \sum_{q_1=0}^{\infty} A_1 \int_0^\infty f_{\gamma_{SR}}(x) \int_0^{L_E x} f_E(y) \int_{\Theta(1+y)-1}^{L_D x} z^{L_D\mu_D + q_1 - 1} \exp(-L_D a_D z) dz dy dx, \end{aligned} \tag{15}$$

where

$$A_1 = (L_D a_D)^{L_D\mu_D} (b_D)^{-L_D m_D} \frac{1}{\Gamma(L_D\mu_D)} \frac{(L_D m_D)_{q_1}}{(L_D\mu_D)_{q_1} q_1!} \left(\frac{L_D a_D k_D \mu_D}{b_D m_D} \right)^{q_1}. \tag{16}$$

We let $\Phi_{11} = \int_{\Theta(1+y)-1}^{L_D x} z^{L_D\mu_D + q_1 - 1} \exp(-L_D a_D z) dz$, with the aid of [43, Eq. (8.310.1)], [39, Eq. (8.352.6)] and [43, Eq. (1.111)], Φ_{11} can be expressed as

$$\Phi_{11} = \left(L_D a_D\right)^{-\left(L_D \mu_D + q_1\right)} (L\mu_D + q_1 - 1)!\Big(\exp\left(-L_D a_D \left(\Theta y + \Theta - 1\right)\right)$$
$$\times \sum_{s2=0}^{L_D \mu_D + q_1 - 1} \frac{L_D{}^{s_2} a_D{}^{s_2} \sum_{t=0}^{s_2} \binom{s_2}{t} \Theta^t (\Theta - 1)^{s_2 - t} y^t}{s_2 !} - \exp\left(-L_D{}^2 a_D x\right) \sum_{s_1=0}^{L\mu_D + q_1 - 1} \frac{\left(L_D{}^2 a_D x\right)^{s_1}}{s_1 !}\Big). \quad (17)$$

Substituting (5), (6) and (17) into (15), after a series of complex integral and algebraic operations, we obtain

$$\Phi_1 = \sum_{q_3=0}^{\infty} A_5 \Delta_1 \left(L_E \mu_E + q_2 + t - 1\right)! \left(\frac{\Gamma\left(\mu_{SR} + q_3\right)}{a_{SR}{}^{\left(\mu_{SR} + q_3\right)}} - \sum_{m_1=0}^{L_E \mu_E + q_2 + t - 1} \frac{L_E{}^{m_1} \left(L_E a_E + L_D a_D \Theta\right)^{m_1}}{m_1 !} \right.$$
$$\left. \times \frac{\Gamma\left(\mu_{SR} + q_3 + m_1\right)}{\left(a_{SR} + L_E L_E a_E + L_E L_D a_D \Theta\right)^{\left(\mu_{SR} + q_3 + m_1\right)}} \right) - \sum_{q_3=0}^{\infty} A_5 \Delta_2 \left(L_E \mu_E + q_2 - 1\right)! \quad (18)$$
$$\times \left(\frac{\Gamma\left(\mu_{SR} + q_3 + s_1\right)}{\left(a_{SR} + L_D{}^2 a_D\right)^{\left(\mu_{SR} + q_3 + s_1\right)}} - \sum_{m_2=0}^{L_E \mu_E + q_2 - 1} \frac{a_E{}^{m_2} L_E{}^{2m_2} \Gamma\left(\mu_{SR} + q_3 + s_1 + m_2\right)}{m_2 ! \left(a_{SR} + L_D{}^2 a_D + L_E{}^2 a_E\right)^{\left(\mu_{SR} + q_3 + s_1 + m_2\right)}} \right),$$

where

$$\Delta_1 = \sum_{q_1=0}^{\infty} A_3 \sum_{q_2=0}^{\infty} A_2 (L_D \mu_D + q_1 - 1)! \exp\left(-L_D a_D \left(\Theta - 1\right)\right)$$
$$\times \sum_{s_2=0}^{L\mu_D + q_1 - 1} \frac{L_D{}^{s_2} a_D{}^{s_2}}{s_2 !} \sum_{t=0}^{s_2} \binom{s_2}{t} \Theta^t (\Theta - 1)^{s_2 - t} \left(L_E a_E + L_D a_D \Theta\right)^{-\left(L_E \mu_E + q_2 + t\right)} \quad (19)$$

$$\Delta_2 = \sum_{q_1=0}^{\infty} A_3 \sum_{q_2=0}^{\infty} A_4 (L\mu_D + q_1 - 1)! \sum_{s_1=0}^{L\mu_D + q_1 - 1} \frac{\left(L_D{}^2 a_D\right)^{s_1}}{s_1 !} \quad (20)$$

and

$$A_2 = \left(L_E a_E\right)^{L_E \mu_E} b_E{}^{-L_E m_E} \frac{(L_E m_E)_{q_2}}{\Gamma(L_E \mu_E)(L_E \mu_E)_{q_2} q_2 !} \left(\frac{L_E a_E k_E \mu_E}{b_E m_E} \right)^{q_2}, \quad (21)$$

$$A_3 = \left(L_D a_D\right)^{-q_1} b_D{}^{-L_D m_D} \frac{(L_D m_D)_{q_1}}{\Gamma(L_D \mu_D)(L_D \mu_D)_{q_1} q_1 !} \left(\frac{L_D a_D k_D \mu_D}{b_D m_D} \right)^{q_1}, \quad (22)$$

$$A_4 = \left(L_E a_E\right)^{-q_2} b_E{}^{-L_E m_E} \frac{(L_E m_E)_{q_2}}{\Gamma(L_E \mu_E)(L_E \mu_E)_{q_2} q_2 !} \left(\frac{L_E a_E k_E \mu_E}{b_E m_E} \right)^{q_2}, \quad (23)$$

$$A_5 = a_{SR}{}^{\mu_{SR}} b_{SR}{}^{-m_{SR}} \frac{1}{\Gamma(\mu_{SR})} \left(\frac{a_{SR} k_{SR} \mu_{SR}}{b_{SR} m_{SR}} \right)^{q_3} \frac{(m_{SR})_{q_3}}{(\mu_{SR})_{q_3} q_3 !}. \quad (24)$$

After analyzing (10), we obtain the expanded expression as

$$\Phi_2 = \Pr\left\{\Theta\left(1 + L_E \gamma_{SR}\right) - 1 < \gamma_D < L_D \gamma_{SR}, \gamma_E > L_E \gamma_{SR}\right\}$$
$$= \int_0^{\infty} f_{\gamma_{SR}}\left(x\right) \int_{L_E x}^{\infty} f_E\left(y\right) \int_{\Theta\left(1 + L_E x\right) - 1}^{L_D x} f_D\left(z\right) dz dy dx. \quad (25)$$

With the help of (5) , (6), [43, Eq. (8.310.1)], [43, Eq. (8.352.6)] and [43, Eq. (1.111)], we can gradually expand the integral, and the final expression of Φ_2 is as

$$\Phi_2 = \Phi_{21} - \Phi_{22} - \Phi_{23} + \Phi_{24} + \Phi_{25} - \Phi_{26}, \tag{26}$$

where

$$\begin{aligned}\Phi_{21} = &\sum_{q_3=0}^{\infty} A_5 \sum_{q_1=0}^{\infty} A_3 \sum_{q_2=0}^{\infty} A_2 \left(L_D\mu_D + q_1 - 1\right)! \frac{\Gamma\left(L_E\mu_E + q_2\right)}{\left(L_E a_E\right)^{(L_E\mu_E + q_2)}} \exp\left(-L_D a_D\left(\Theta - 1\right)\right) \\ &\times \sum_{s2=0}^{L_D\mu_D + q_1 - 1} \frac{\left(L_D a_D\right)^{s_2}}{s_2!} \sum_{t=0}^{s_2} \binom{s_2}{t} \left(\Theta L_E\right)^t \left(\Theta - 1\right)^{s_2 - t} \frac{\Gamma\left(\mu_{SR} + q_3 + t\right)}{\left(a_{SR} + L_D a_D \Theta L_E\right)^{\mu_{SR} + q_3 + t}},\end{aligned} \tag{27}$$

$$\begin{aligned}\Phi_{22} = &\sum_{q_3=0}^{\infty} A_5 \sum_{q_1=0}^{\infty} A_3 \sum_{q_2=0}^{\infty} A_2 \left(L_D\mu_D + q_1 - 1\right)! \frac{\Gamma\left(L_E\mu_E + q_2\right)}{\left(L_E a_E\right)^{(L_E\mu_E + q_2)}} \\ &\times \sum_{s_1=0}^{L_D\mu_D + q_1 - 1} \frac{\left(L_D{}^2 a_D\right)^{s_1}}{s_1!} \frac{\Gamma\left(\mu_{SR} + q_3 + s_1\right)}{\left(a_{SR} + L_D{}^2 a_D\right)^{\mu_{SR} + q_3 + s_1}},\end{aligned} \tag{28}$$

$$\begin{aligned}\Phi_{23} = &\sum_{q_3=0}^{\infty} A_5 \sum_{q_1=0}^{\infty} A_3 \sum_{q_2=0}^{\infty} A_4 \left(L_D\mu_D + q_1 - 1\right)! \left(L_E\mu_E + q_2 - 1\right)! \exp\left(-L_D a_D\left(\Theta - 1\right)\right) \\ &\times \sum_{s_2=0}^{L_D\mu_D + q_1 - 1} \frac{\left(L_D a_D\right)^{s_2}}{s_2!} \sum_{t=0}^{s_2} \binom{s_2}{t} \left(\Theta L_E\right)^t \left(\Theta - 1\right)^{s_2 - t} \frac{\Gamma\left(\mu_{SR} + q_3 + t\right)}{\left(a_{SR} + L_D a_D \Theta L_E\right)^{\mu_{SR} + q_3 + t}},\end{aligned} \tag{29}$$

$$\begin{aligned}\Phi_{24} = &\sum_{q_3=0}^{\infty} A_5 \sum_{q_1=0}^{\infty} A_3 \sum_{q_2=0}^{\infty} A_4 \left(L_D\mu_D + q_1 - 1\right)! \left(L_E\mu_E + q_2 - 1\right)! \\ &\times \sum_{s_1=0}^{L_D\mu_D + q_1 - 1} \frac{\left(L_D{}^2 a_D\right)^{s_1}}{s_1!} \frac{\Gamma\left(\mu_{SR} + q_3 + s_1\right)}{\left(a_{SR} + L_D{}^2 a_D\right)^{\mu_{SR} + q_3 + s_1}},\end{aligned} \tag{30}$$

$$\begin{aligned}\Phi_{25} = &\sum_{q_3=0}^{\infty} A_5 \sum_{q_1=0}^{\infty} A_3 \sum_{q_2=0}^{\infty} A_4 \left(L_D\mu_D + q_1 - 1\right)! \left(L_E\mu_E + q_2 - 1\right)! \exp\left(-L_D a_D\left(\Theta - 1\right)\right) \\ &\times \sum_{s_2=0}^{L_D\mu_D + q_1 - 1} \frac{\left(L_D a_D\right)^{s_2}}{s_2!} \sum_{t=0}^{s_2} \binom{s_2}{t} \left(\Theta L_E\right)^t \left(\Theta - 1\right)^{s_2 - t} \\ &\times \sum_{m_1=0}^{L_E\mu_E + q_2 - 1} \frac{\left(L_E{}^2 a_E\right)^{m_1}}{m_1!} \frac{\Gamma\left(\mu_{SR} + q_3 + t + m_1\right)}{\left(a_{SR} + L_D a_D \Theta L_E + L_E{}^2 a_E\right)^{\mu_{SR} + q_3 + t + m_1}},\end{aligned} \tag{31}$$

$$\begin{aligned}\Phi_{26} = &\sum_{q_3=0}^{\infty} A_5 \sum_{q_1=0}^{\infty} A_3 \sum_{q_2=0}^{\infty} A_4 (L_D\mu_D + q_1 - 1)! \left(L_E\mu_E + q_2 - 1\right)! \\ &\times \sum_{s_1=0}^{L_D\mu_D + q_1 - 1} \frac{\left(L_D{}^2 a_D\right)^{s_1}}{s_1!} \sum_{m_1=0}^{L_E\mu_E + q_2 - 1} \frac{\left(L_E{}^2 a_E\right)^{m_1}}{m_1!} \frac{\Gamma\left(\mu_{SR} + q_3 + s_1 + m_1\right)}{\left(a_{SR} + L_D{}^2 a_D + L_E{}^2 a_E\right)^{\mu_{SR} + q_3 + s_1 + m_1}}.\end{aligned} \tag{32}$$

For the third case, the calculation of Φ_3 can be expressed as

$$\begin{aligned}\Phi_3 &= \Pr\left\{1+L_D\gamma_{SR} > \Theta\left(1+\gamma_E\right), L_D\gamma_{SR} < \gamma_D, L_E\gamma_{SR} > \gamma_E\right\} \\ &= \Pr\left\{\gamma_E < \frac{1+L_D\gamma_{SR}-\Theta}{\Theta}, L_D\gamma_{SR} < \gamma_D\right\} \\ &= \int_0^\infty f_{\gamma_{SR}}\left(x\right)\int_0^{\frac{1+L_Dx-\Theta}{\Theta}} f_E\left(y\right)\int_{L_Dx}^\infty f_D\left(z\right)dzdydx \\ &= \int_0^\infty f_{\gamma_{SR}}\left(x\right)\int_0^{\frac{1+L_Dx-\Theta}{\Theta}} f_E\left(y\right)\left(\int_0^\infty f_D\left(z\right)dz - \int_0^{L_Dx} f_D\left(z\right)dz\right)dydx.\end{aligned} \tag{33}$$

In (33), Φ_3 contains triple integrals, similar to the derivation of Φ_1, and making use of [43, Eq. (3.326.2)], we obtain the expression of Φ_3 as

$$\Phi_3 = \sum_{q_3=0}^\infty A_5 \sum_{q_1=0}^\infty A_1 \sum_{q_2=0}^\infty A_4 \left(L_E\mu_E + q_2 - 1\right)!\left(\Phi_{31} - \Phi_{32}\right), \tag{34}$$

where

$$\begin{aligned}\Phi_{31} = &\left(\left(\frac{\Gamma\left(L_D\mu_D+q_1\right)}{\left(L_Da_D\right)^{\left(L_D\mu_D+q_1\right)}} - \left(L_Da_D\right)^{-\left(L_D\mu_D+q_1\right)}\left(L_D\mu_D+q_1-1\right)!\right)\frac{\Gamma\left(\mu_{SR}+q_3\right)}{a_{SR}^{\left(\mu_{SR}+q_3\right)}}\right. \\ &\left. + \left(L_Da_D\right)^{-\left(L_D\mu_D+q_1\right)}\left(L_D\mu_D+q_1-1\right)! \sum_{s_1=0}^{L_D\mu_D+q_1-1} \frac{\left(L_D{}^2a_D\right)^{s_1}\Gamma\left(\mu_{SR}+q_3+s_1\right)}{s_1!\left(a_{SR}+L_D{}^2a_D\right)^{\left(\mu_{SR}+q_3+s_1\right)}}\right),\end{aligned} \tag{35}$$

$$\begin{aligned}\Phi_{32} = &\exp\left(\frac{L_Ea_E\left(\Theta-1\right)}{\Theta}\right)\sum_{s_2=0}^{L_E\mu_E+q_2-1}\frac{\left(L_Ea_E\right)^{s_2}}{\Theta^{s_2}s_2!}\sum_{t=0}^{s_2}\binom{s_2}{t}L_D{}^t\left(1-\Theta\right)^{s_2-t}\left(\left(\frac{\Gamma\left(L_D\mu_D+q_1\right)}{\left(L_Da_D\right)^{\left(L_D\mu_D+q_1\right)}}\right.\right. \\ &\left.-\left(L_Da_D\right)^{-\left(L_D\mu_D+q_1\right)}\left(L_D\mu_D+q_1-1\right)!\right)\frac{\Gamma\left(\mu_{SR}+q_3+t\right)}{\left(a_{SR}+\frac{L_Ea_EL_D}{\Theta}\right)^{\left(\mu_{SR}+q_3+t\right)}} + \left(L_Da_D\right)^{-\left(L_D\mu_D+q_1\right)} \\ &\left.\times\left(L_D\mu_D+q_1-1\right)!\sum_{s_1=0}^{L_D\mu_D+q_1-1}\frac{\left(L_D{}^2a_D\right)^{s_1}\Gamma\left(\mu_{SR}+q_3+t+s_1\right)}{s_1!\left(a_{SR}+\frac{L_Ea_EL_D}{\Theta}+L_D{}^2a_D\right)^{\left(\mu_{SR}+q_3+t+s_1\right)}}\right).\end{aligned} \tag{36}$$

Similarly, we have

$$\begin{aligned}\Phi_4 = &\sum_{q3=0}^\infty A_5\sum_{q_1=0}^\infty A_1\sum_{q_2=0}^\infty A_2\sum_{s_1=0}^{L_D\mu_D+q_1-1}\frac{\left(L_D\mu_D+q_1-1\right)!L_D{}^{s_1}}{s_1!\left(L_Da_D\right)^{L_D\mu_D+q_1-s_1}} \\ &\times\sum_{s_2=0}^{L_E\mu_E+q_2-1}\frac{\left(L_E\mu_E+q_2-1\right)!L_E{}^{s_2}\left(a_{SR}+L_D{}^2a_D+L_E{}^2a_E\right)^{-\left(\mu_{SR}+q_3+s_1+s_2\right)}}{s_2!\left(L_Ea_E\right)^{L_E\mu_E+q_2-s_2}} \\ &\times\Gamma\left(\mu_{SR}+q_3+s_1+s_2, \frac{\left(a_{SR}+L_D{}^2a_D+L_E{}^2a_E\right)\left(\Theta-1\right)}{L_D-\Theta L_E}\right).\end{aligned} \tag{37}$$

According to (7), (18), (25), (34) and (37), under the premise that $L_D \le L_E$ exists, we finally express SOP as

$$SOP = 1-\left(\Phi_1+\Phi_3\right). \tag{38}$$

When $L_D > L_E$ is satisfied, the SOP can be expressed as

$$SOP = 1 - \left(\Phi_1 + \Phi_2 + \Phi_3 + \Phi_4\right). \tag{39}$$

4. SPSC Analysis

In this section, we discuss another fundamental criterion in wireless environments, i.e., SPSC, which is defined as the probability of taking positive value of instantaneous safety capacity in [45]. The SPSC can be expressed as

$$\begin{aligned} SPSC &= P\left\{C_S\left(\gamma_D, \gamma_E\right) > 0\right\} \\ &= P\left\{1 + \min\left(L_D \gamma_{SR}, \gamma_D\right) > 1 + \min\left(L_E \gamma_{SR}, \gamma_E\right)\right\} \\ &= P\left\{\min\left(L_D \gamma_{SR}, \gamma_D\right) > \min\left(L_E \gamma_{SR}, \gamma_E\right)\right\}. \end{aligned} \tag{40}$$

For the relationship of $\left(L_D\gamma_{SR}, \gamma_D\right)$ and $\left(L_E\gamma_{SR}, \gamma_E\right)$, we can explain it in four cases: i) $L_D\gamma_{SR} > \gamma_D, L_E\gamma_{SR} > \gamma_E$; ii) $L_D\gamma_{SR} > \gamma_D, L_E\gamma_{SR} < \gamma_E$; iii) $L_D\gamma_{SR} < \gamma_D, L_E\gamma_{SR} > \gamma_E$; iv) $L_D\gamma_{SR} < \gamma_D, L_E\gamma_{SR} < \gamma_E$. It should be noted that he second and fourth cases are impossible events under the condition of $L_D \le L_E$. But if $L_D > L_E$, all four cases are necessary.

The integral expansion of I_1 is

$$\begin{aligned} I_1 &= P\left\{L_D\gamma_{SR} > \gamma_D > \gamma_E, \gamma_E < L_E\gamma_{SR}\right\} \\ &= \int_0^\infty f_{\gamma_{SR}}(x) \int_0^{L_E x} f_E(y) \int_y^{L_D x} f_D(z)\, dz dy dx. \end{aligned} \tag{41}$$

With the help of (5), (6), [43, Eq. (8.310.1)] and [43, Eq. (8.352.6)], I_1 is derived as

$$\begin{aligned} I_1 &= \sum_{q_3=0}^{\infty} A_5 \Psi_1 \left(L_E\mu_E + q_2 + s_2 - 1\right)! \\ &\times \left(\frac{\Gamma\left(\mu_{SR} + q_3\right)}{{a_{SR}}^{(\mu_{SR}+q_3)}} - \sum_{m_1=0}^{L_E\mu_E+q_2+s_2-1} \frac{{L_E}^{m_1}\left(L_E a_E + L_D a_D\right)^{m_1} \Gamma\left(\mu_{SR} + q_3 + m_1\right)}{m_1!\left(a_{SR} + L_E L_E a_E + L_E L_D a_D\right)^{(\mu_{SR}+q_3+m_1)}} \right) \\ &- \sum_{q_3=0}^{\infty} A_5 \Psi_2 \left(L_E\mu_E + q_2 - 1\right)! \\ &\times \left(\frac{\Gamma\left(\mu_{SR} + q_3 + s_1\right)}{\left(a_{SR} + {L_D}^2 a_D\right)^{(\mu_{SR}+q_3+s_1)}} - \sum_{m_2=0}^{L_E\mu_E+q_2-1} \frac{\left({L_E}^2 a_E\right)^{m_2} \Gamma\left(\mu_{SR} + q_3 + s_1 + m_2\right)}{m_2!\left(a_{SR} + {L_D}^2 a_D + {L_E}^2 a_E\right)^{(\mu_{SR}+q_3+s_1+m_2)}} \right), \end{aligned} \tag{42}$$

where

$$\Psi_1 = \sum_{q_1=0}^{\infty} A_3 \sum_{q_2=0}^{\infty} A_2 (L_D\mu_D + q_1 - 1)! \sum_{s_2=0}^{L_D\mu_D+q_1-1} \frac{{L_D}^{s_2} {a_D}^{s_2}}{s_2!} \left(L_E a_E + L_D a_D\right)^{-(L_E\mu_E+q_2+s_2)}, \tag{43}$$

and

$$\Psi_2 = \sum_{q_1=0}^{\infty} A_3 \sum_{q_2=0}^{\infty} A_4 (L_D\mu_D + q_1 - 1)! \sum_{s_1=0}^{L_D\mu_D+q_1-1} \frac{\left({L_D}^2 a_D\right)^{s_1}}{s_1!}. \tag{44}$$

Similar to the derivation of I_1, I_2 is obtained as

$$
\begin{aligned}
I_2 &= P\left\{L_D\gamma_{SR} > \gamma_D > L_E\gamma_{SR}, \gamma_E < L_E\gamma_{SR}\right\} \\
&= \sum_{q_3=0}^{\infty} A_5 \sum_{q_1=0}^{\infty} A_3 \sum_{q_2=0}^{\infty} A_4 (L_D\mu_D + q_1 - 1)!(L_E\mu_E + q_2 - 1)! \\
&\times\left(\left(\sum_{s2=0}^{L_D\mu_D+q_1-1} \frac{\left(L_D a_D L_E\right)^{s_2}\Gamma\left(\mu_{SR}+q_3+s_2\right)}{s_2!\left(a_{SR}+L_D a_D L_E\right)^{\left(\mu_{SR}+q_3+s_2\right)}} - \sum_{s_1=0}^{L_D\mu_D+q_1-1} \frac{\left(L_D{}^2 a_D\right)^{s_1}\Gamma\left(\mu_{SR}+q_3+s_1\right)}{s_1!\left(a_{SR}+L_D{}^2 a_D\right)^{\left(\mu_{SR}+q_3+s_1\right)}}\right)\right. \\
&-\left(\sum_{s_3=0}^{L_E\mu_E+q_2-1} \frac{\left(L_E{}^2 a_E\right)^{s_3}}{s_3!} \sum_{s2=0}^{L_D\mu_D+q_1-1} \frac{\left(L_D a_D L_E\right)^{s_2}\Gamma\left(\mu_{SR}+q_3+s_3+s_2\right)}{s_2!\left(a_{SR}+L_E{}^2 a_E+L_D a_D L_E\right)^{\left(\mu_{SR}+q_3+s_3+s_2\right)}}\right. \\
&\left.\left.-\sum_{s_3=0}^{L_E\mu_E+q_2-1} \frac{\left(L_E{}^2 a_E\right)^{s_3}}{s_3!} \sum_{s_1=0}^{L_D\mu_D+q_1-1} \frac{\left(L_D{}^2 a_D\right)^{s_1}\Gamma\left(\mu_{SR}+q_3+s_3+s_1\right)}{s_1!\left(a_{SR}+L_D{}^2 a_D+L_E{}^2 a_E\right)^{\left(\mu_{SR}+q_3+s_3+s_1\right)}}\right)\right).
\end{aligned} \tag{45}
$$

I_3 can be written as

$$
\begin{aligned}
I_3 &= P\left\{\gamma_E < L_E\gamma_{SR}, L_D\gamma_{SR} < \gamma_D\right\} \\
&= \sum_{q_3=0}^{\infty} A_5 \sum_{q_1=0}^{\infty} A_1 \sum_{q_2=0}^{\infty} A_4 \left(L_E\mu_E + q_2 - 1\right)! \\
&\times\left(\left(\left(\frac{\Gamma\left(L_D\mu_D+q_1\right)}{\left(L_D a_D\right)^{\left(L_D\mu_D+q_1\right)}} - A_6\right)\frac{\Gamma\left(\mu_{SR}+q_3\right)}{a_{SR}{}^{\left(\mu_{SR}+q_3\right)}} + A_6 \sum_{s_1=0}^{L_D\mu_D+q_1-1} \frac{\left(L_D{}^2 a_D\right)^{s_1}\Gamma\left(\mu_{SR}+q_3+s_1\right)}{s_1!\left(a_{SR}+L_D{}^2 a_D\right)^{\left(\mu_{SR}+q_3+s_1\right)}}\right.\right. \\
&-\sum_{s_2=0}^{L_E\mu_E+q_2-1} \frac{\left(L_E{}^2 a_E\right)^{s_2}}{s_2!}\left(\left(\frac{\Gamma\left(L_D\mu_D+q_1\right)}{\left(L_D a_D\right)^{\left(L_D\mu_D+q_1\right)}} - A_6\right)\frac{\Gamma\left(\mu_{SR}+q_3+s_2\right)}{\left(a_{SR}+L_E{}^2 a_E\right)^{\left(\mu_{SR}+q_3+s_2\right)}}\right. \\
&\left.\left.+A_6 \sum_{s_1=0}^{L_D\mu_D+q_1-1} \frac{\left(L_D{}^2 a_D\right)^{s_1}\Gamma\left(\mu_{SR}+q_3+s_2+s_1\right)}{s_1!\left(a_{SR}+L_E{}^2 a_E+L_D{}^2 a_D\right)^{\left(\mu_{SR}+q_3+s_2+s_1\right)}}\right)\right),
\end{aligned} \tag{46}
$$

where

$$
A_6 = \left(L_D a_D\right)^{-\left(L_D\mu_D+q_1\right)}\left(L_D\mu_D + q_1 - 1\right)!. \tag{47}
$$

The expression of I_4 is

$$
\begin{aligned}
I_4 &= P\left\{\gamma_E < L_E\gamma_{SR}, \gamma_D < L_D\gamma_{SR}\right\} \\
&= \sum_{q_1=0}^{\infty} A_3 \sum_{q_2=0}^{\infty} A_4 \left(L_D\mu_D + q_1 - 1\right)!\left(L_E\mu_E + q_2 - 1\right)! \\
&\times\left(\left(\frac{\Gamma\left(\mu_{SR}+q_3\right)}{a_{SR}{}^{\mu_{SR}+q_3}} - \sum_{s_1=0}^{L_D\mu_D+q_1-1} \frac{\left(L_D{}^2 a_D\right)^{s_1}\Gamma\left(\mu_{SR}+q_3+s_1\right)}{s_1!\left(a_{SR}+L_D{}^2 a_D\right)^{\mu_{SR}+q_3}}\right) - \sum_{s_2=0}^{L_E\mu_E+q_2-1} \frac{\left(L_E{}^2 a_E\right)^{s_2}}{s_2!}\right. \\
&\left.\times\left(\frac{\Gamma\left(\mu_{SR}+q_3+s_2\right)}{\left(a_{SR}+L_E{}^2 a_E\right)^{\mu_{SR}+q_3+s_2}} - \sum_{s_1=0}^{L_D\mu_D+q_1-1} \frac{\left(L_D{}^2 a_D\right)^{s_1}\Gamma\left(\mu_{SR}+q_3+s_1+s_2\right)}{s_1!\left(a_{SR}+L_D{}^2 a_D+L_E{}^2 a_E\right)^{\mu_{SR}+q_3+s_1+s_2}}\right)\right).
\end{aligned} \tag{48}
$$

Based on (40), (42), (45), (46) and (48), we deduce the closed-form expressions for SPSC under two kinds of multi-antenna conditions: i) $SPSC = I_1 + I_3,\ L_D \le L_E$; ii) $SPSC = I_1 + I_2 + I_3 + I_4,\ L_D > L_E$.

5. Numerical results

In this section, we provide some numerical examples of the analytical expressions derived above and Monte Carlo simulations. From the simulation results illustrated in **Figs. 2-11**, we can see that the theoretical and simulated results are well coincident and the secrecy performance improves with the increase of Ω_{SR} which represents the average SNR of link $S \to R$. It should be noted that same parameters in all simulations are set as follows: $L_D = L_E = L$ in **Figs. 2-9**, $C_{th} = 0.01$ dB, $\Omega_{SR} = \Omega_{D_j}$ and $\Omega_{E_j} = 10$ dB, where $j = 0,1,\cdots,L$. In addition, the number of pseudo-random variables of channel gain is 10^6, and after simulation verification, the condition of infinite series convergence is that the value of cyclic variable is more than 60 times. It should be noted that in the following figures, under the same abscissa, lower SOP and higher SPSC mean good security performance, and vice versa.

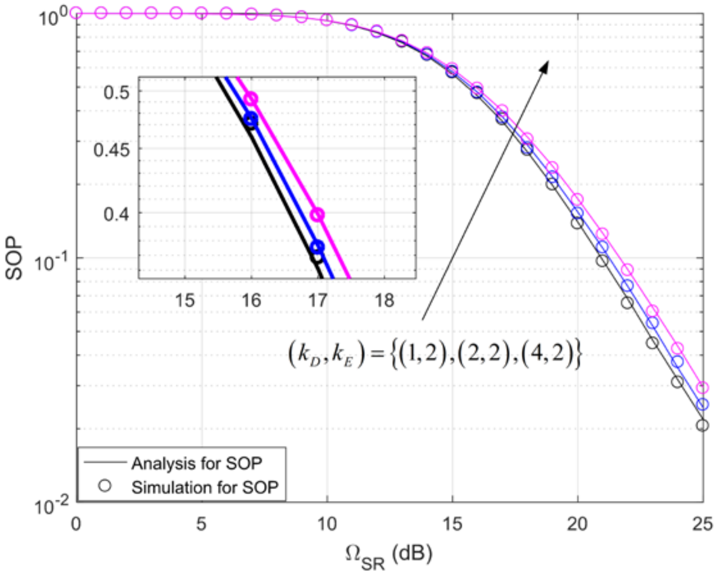

Fig. 2. SOP versus Ω_{SR} for various values of (k_D, k_E) when $\mu_D = \mu_E = 2$, $m_D = m_E = 1$, $L = 2$.

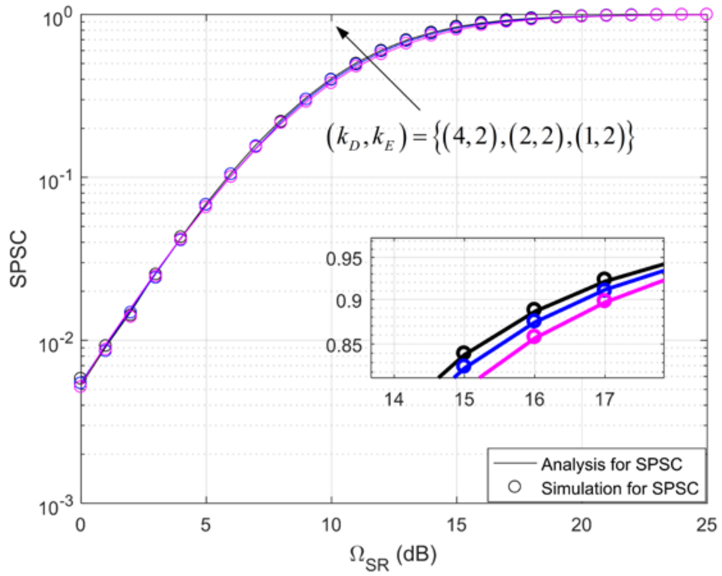

Fig. 3. SPSC versus Ω_{SR} for various values of (k_D,k_E) when $\mu_D=\mu_E=2$, $m_D=m_E=1$, $L=2$.

Fig. 2 and **Fig. 3** depict the curves of SOP and SPSC versus Ω_{SR} for different (k_D,k_E) that k_i denote the ratio of the total energy between the main wave and the scattering components in the legitimate link and wiretapping link. When $\Omega_{SR}>10$ dB, the larger ratio of (k_D,k_E) corresponds to the higher value of SOP and the lower value of SPSC. However, the change of SPSC is not obvious compared with that of SOP. To sum up, under the premise of constant k_E and larger Ω_{SR}, large k_D will damage the security performance of the relay model under consideration .

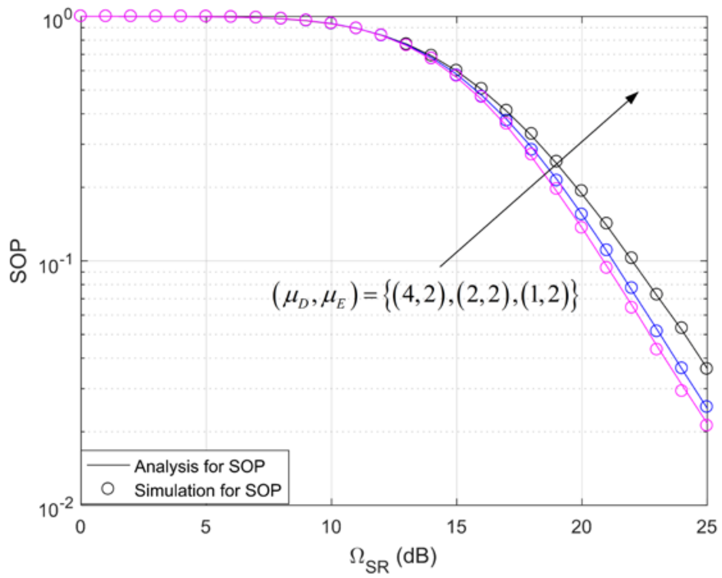

Fig. 4. SOP versus Ω_{SR} for various values of (μ_D,μ_E) when $k_D=k_E=2$, $m_D=m_E=1$, $L=2$.

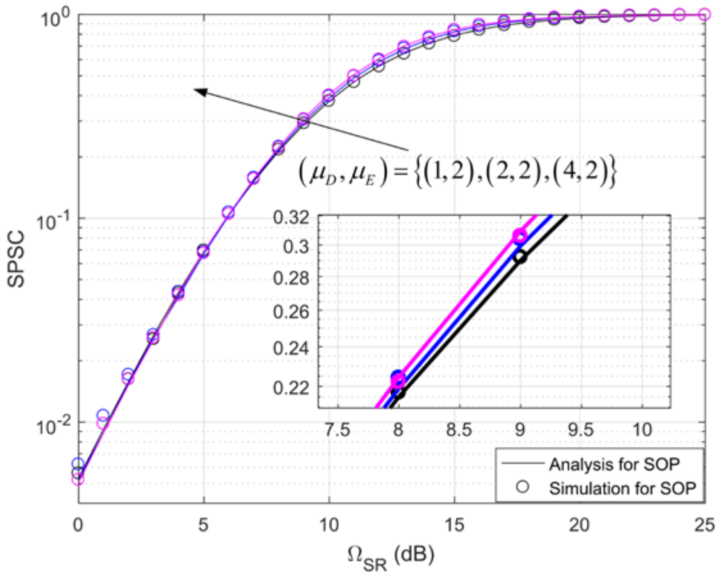

Fig. 5. SPSC versus Ω_{SR} for various values of (μ_D, μ_E) when $k_D = k_E = 2$, $m_D = m_E = 1$, $L = 2$.

Given by **Fig. 4**, the SOP versus Ω_{SR} for various values of (μ_D, μ_E) is provided, where μ_D and μ_E are the quantity for multipath clusters of the legitimate link and wiretapping link. We find that the SOP increases gradually with the decrease of μ_D when $\Omega_{SR} > 10$ dB. When $\Omega_{SR} < 10$ dB, the values of SOP and SPSC have barely changed. From **Fig. 5**, it can be seen that the increase of μ_D will lead to an increasing SPSC. Therefore, we obtain that the improvement of security performance needs large ratio of (μ_D, μ_E) when $\Omega_{SR} > 10$ dB.

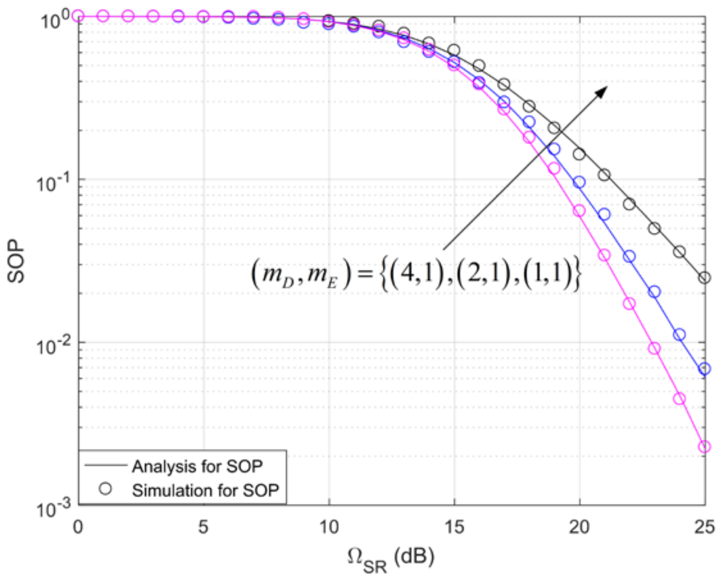

Fig. 6. SOP versus Ω_{SR} for various values of (m_D, m_E) when $k_D = k_E = 2$, $\mu_D = \mu_E = 2$, $L = 2$.

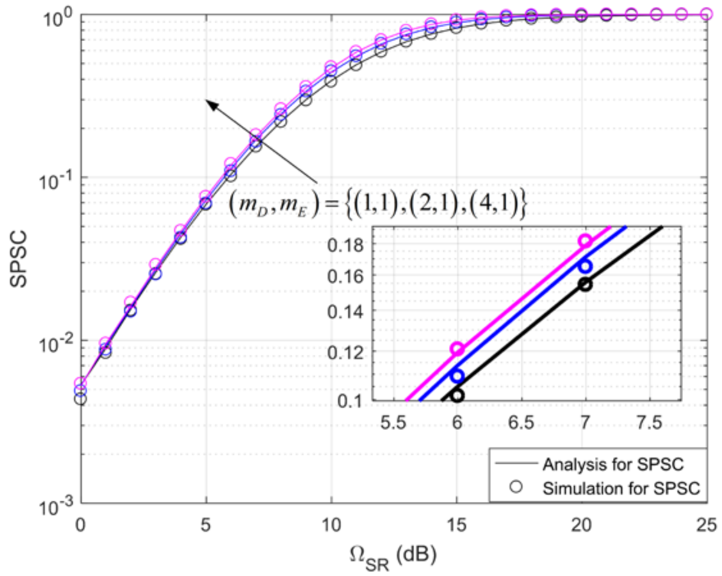

Fig. 7. SPSC versus Ω_{SR} for various values of (m_D, m_E) when $k_D = k_E = 2$, $\mu_D = \mu_E = 2$, $L = 2$.

Fig. 6 and **Fig. 7** describe the SOP and SPSC with changing (m_D, m_E) versus Ω_{SR}, in which m_i denotes the shaping parameter of Nakagami-m random variable (RV). In **Fig. 6**, under the condition that $\Omega_{SR} > 10$ dB exists, when the value of m_D decreases, the value of SOP increases. In **Fig. 7**, increasing m_D will yield increasing SPSC. That is to say, larger (m_D, m_E) is beneficial to the improvement of confidentiality on the premise of high SNR regime.

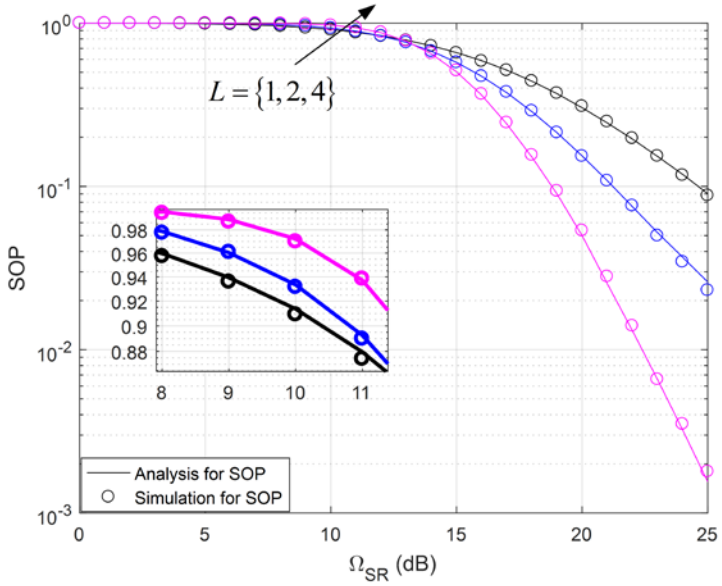

Fig. 8. SOP versus Ω_{SR} for various values of L when $k_D = k_E = 2$, $\mu_D = \mu_E = 2$, $m_D = m_E = 1$.

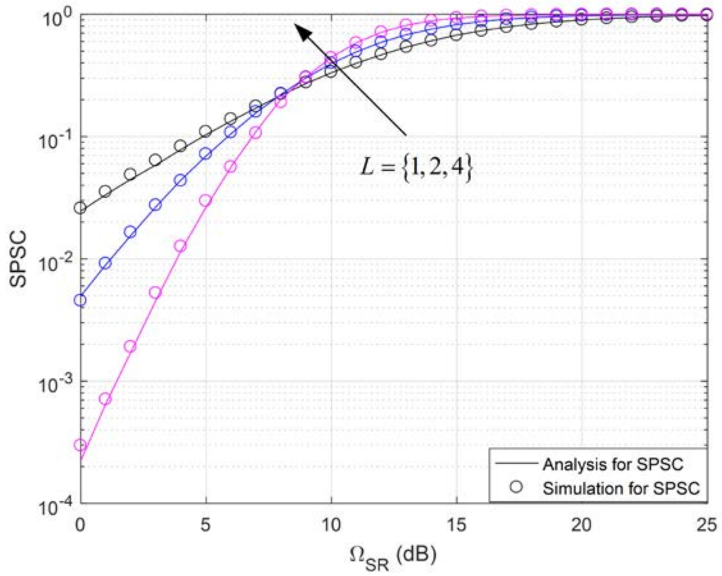

Fig. 9. SPSC versus Ω_{SR} for various values of L when $k_D = k_E = 2$, $\mu_D = \mu_E = 2$, $m_D = m_E = 1$.

As shown in **Fig. 8** and **Fig. 9**, we present the change of SOP and SPSC versus Ω_{SR} against different values of L, From **Fig. 8**, we can observe that when $\Omega_{SR} > 13$ dB, the SOP increases with the falling L, and vice versa. In **Fig. 9**, we can see that the value of SPSC increases as increasing L with $\Omega_{SR} > 8$ dB, and vice versa. The above facts show that in larger SNR regime, the increasing number of antennas is conducive to the improvement of confidentiality in considered relay network, while under smaller SNR regime, the increasing number of antennas causes the decrease of secrecy performance.

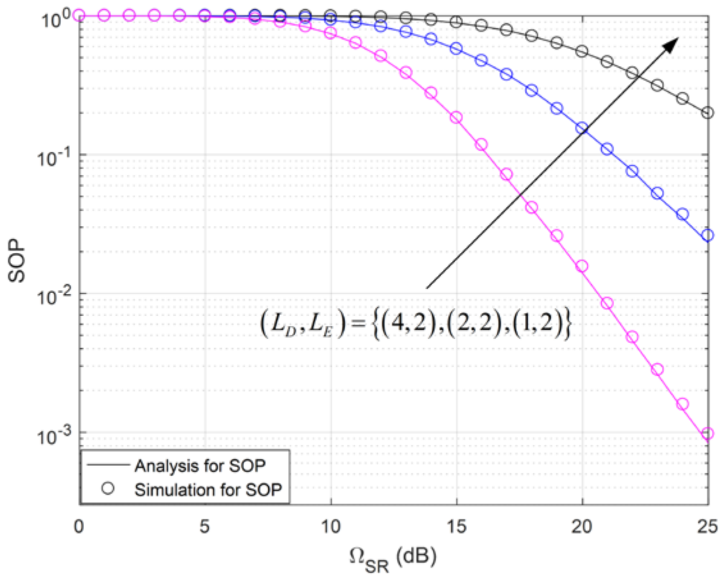

Fig. 10. SPSC versus Ω_{SR} for various values of (L_D, L_E) when $k_D = k_E = 2$, $\mu_D = \mu_E = 2$, $m_D = m_E = 1$.

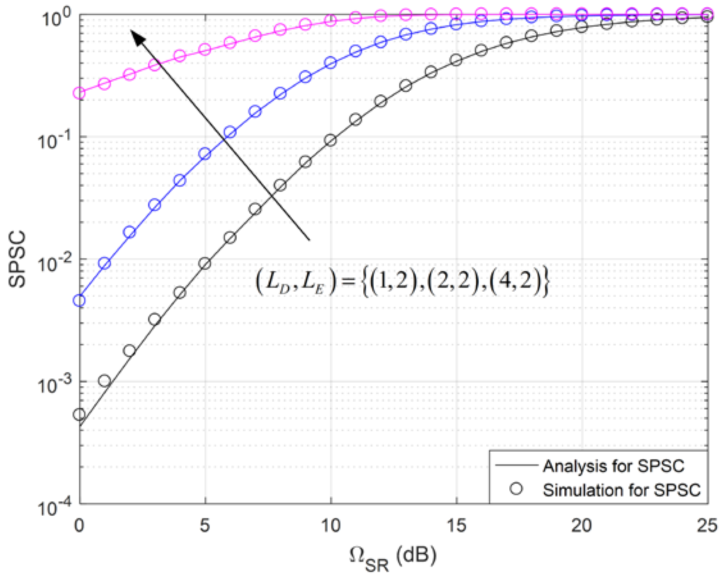

Fig. 11. SPSC versus Ω_{SR} for various values of (L_D, L_E) when $k_D = k_E = 2$, $\mu_D = \mu_E = 2$, $m_D = m_E = 1$.

Fig. 10 and **Fig. 11** illustrate the changes of SOP and SPSC with $L_D \neq L_E$, We can find that when the values of other parameters are the same, under $\Omega_{SR} > 5$ dB, the SOP takes a smaller value with the increase of the ratio of (L_D, L_E), while the value of SPSC is larger under arbitrary Ω_{SR} and larger ratio of (L_D, L_E). It can be obtained that when the number of antennas at the legitimate terminal is larger than that at the eavesdropper, the security capability can be significantly improved.

6. Conclusion

In this paper, we explore PLS for WCNs over κ-μ shadowed fading channels in term of SOP and SPSC. Based on the proposed SIMO DF relay model, the new theoretical expressions for SOP and SPSC are derived with concise functions. Furthermore, the numerical results are provided to verify the correctness of our theoretical analysis, and the simulation results illustrate that: i) large ratio of (μ_D, μ_E) and (m_D, m_E) can enhance security performance of the considering relay network, while large ratio of (k_D, k_E) will reduce the confidentiality of the model. ii) Under the premise of high SNR, large ratio of (L_D, L_E) contributes to the improvement of secrecy performance, and vice versa.

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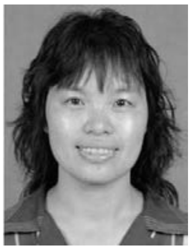

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