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# Secrecy Analysis in SWIPT Systems Over Generalized-$K$ Fading Channels

Zhijie Wang, Hui Zhao, Shuai Wang, Jiankang Zhang, and Mohamed-Slim Alouini

***Abstract*—In this letter, we investigate the secrecy performance of the simultaneous wireless information and power transfer (SWIPT) system over generalized-$K$ fading channels. After analyzing the communications scenario, we derive the closed-form expression for the secrecy outage probability (SOP), and give some simplified expressions for SOP in some special cases. Effective secrecy throughput is also investigated to capture the amount of secure transmitted information. To derive the diversity order, the asymptotic SOP is also analyzed when the average signal-to-noise ratio is large sufficiently. Finally, numerical results are used to validate the correctness of our derived expressions.**

***Index Terms*—Effective secrecy throughput, secrecy outage probability, SWIPT, and generalized-$K$ fading channels.**

## I. Introduction

Some simultaneous wireless information and power transfer (SWIPT) based transmission schemes have recently received significant attention [1], because SWIPT acts as an alternative method to prolong the lifetime of energy-constrained communication works and energy supply. Although power control can also extend the battery's lifetime, the system has to use self-energy, so the effect of extending battery's lifetime is limited, compared to SWIPT. Under SWIPT schemes, time switching (TS) method in [2] was proposed to decode information and extract power simultaneously through communications. The harvesting receiver switches in time between harvesting energy and decoding information in TS systems.

Due to the open access in wireless communications [3], [4], physical layer security is an unavoidable and important issue in SWIPT systems [5]-[7]. [5]-[7] investigated the secrecy performance of SWIPT systems over Rayleigh fading channels, i.e., small-scale fading. However, the shadowing impact should be also considered in the power transfer system in wireless communications, which accounts for the large-scale fading. The composite fading (small-scale fading plus large-scale fading) should be investigated in SWIPT systems to capture the wireless fading channel more accurately.

Shadowing is usually modeled by a log-normal distributed random variable. However, there is normally no closed-form expression for some important metrics, such as secrecy outage probability (SOP), in many common communications scenarios [8]. [9] proposed a $K$ distributed variable to approximate the log-normal variable, which is known as generalized-$K$ (GK) fading model. Moreover, small-scale fading is modeled by Nakagami-$m$ distribution in GK fading model. However, the final expressions for some metrics usually include Meijer-G or other special functions, and the Meijer-G function is not viewed as a closed-form in many cases, especially in the engineering field [10]. To make the GK model more tractable, an approximate GK model was proposed in [11] by approximating the form $\int_0^\infty \exp(-t) g(t)\, dt$ as $\sum_{i=1}^{L} \omega_i g(t_i)$, where $t_i$, $\omega_i$ and $L$ are the abscissas, weight factor, and number of summation terms for the Gaussian-Laguerre integration, respectively. This approximation involves only elementary functions, and the high accuracy has been proved in [11].

In this letter, the secrecy performance of TS SWIPT systems is investigated in terms of SOP. Some simplified expressions for SOP are provided in some special cases, including the high signal-to-noise ratio (SNR) region of the main link, which gives us some important and useful insights in the secrecy outage performance of SWIPT systems. Moreover, in order to capture the amount of secure transmitted information, the effective secrecy throughput (EST) is also investigated.

## II. System Model

### A. Communications Scenario

In the TS SWIPT system, a source ($S$) has limited energy due to its small size, such as the sensor in wireless sensor communications, and needs to acquire energy from a beacon ($B$) to delivery its information bits to a destination ($D$). $S$ employs self-energy for channel estimation of $S-D$ link, and harvests energy for signal transmission. However, an eavesdropper ($E$) wants to overhear the transmitted information from $S$ to $D$.

From [2], the received energy of $S$ from $B$ is $E_S = P_B g_{BS} T_1$, where $T_1$ is the duration of energy harvesting, $P_B$ is the transmit power of $B$, and $g_{BS}$ is the channel power gain between $S$ and $B$.

After acquiring adequate energy, the transmit power ($P_S$) from $S$ to $D$ can be given as $P_S = \frac{E_S}{T_2} = \frac{P_B g_{BS} T_1}{T_2}$, where $T_2$ is the duration of the signal transmission.

Thus, the SNRs at $D$ and $E$ are

$$\gamma_D = \frac{P_S g_{SD}}{N_0} = \frac{P_B T_1 g_{BS} g_{SD}}{N_0 T_2} = \alpha g_{BS} g_{SD}, \tag{1}$$

$$\gamma_E = \frac{P_S g_{SE}}{N_0} = \frac{P_B T_1 g_{BS} g_{SE}}{N_0 T_2} = \alpha g_{BS} g_{SE}, \tag{2}$$

respectively, where $\alpha = \frac{P_B T_1}{N_0 T_2}$, $N_0$ is the Gaussian noise power, and $g_{SD}$ (or $g_{SE}$) is the channel power gain of $S-D$ link (or $S-E$ link).

### B. Channel Model

We assume that all links undergo independent GK fading, where the probability density function (PDF) and cumulative

Manuscript received Dec. 28, 2018; revised Feb. 26, 2019; accepted March 15, 2019. The associate editor coordinating the review of this letter and approving it for publication was Glauber Brante.

Z. Wang is with the School of Science, Nanjing University of Science and Technology, and with the ITS of CAST, P. R. China.

H. Zhao and M.-S. Alouini are with the Computer, Electrical and Mathematical Science and Engineering Division, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia.

S. Wang (*corresponding author*: swang@bit.edu.cn) is with the School of Information and Electronics, Beijing Institute of Technology, P. R. China.

J. Zhang is with University of Southampton Faculty of Physical Sciences and Engineering, Southampton, UK SO17 1BJ.

This research was supported in part by the National Science Foundation under contract U1636125, U1836201, 61571401, 61471360 and 61401372, by the Research Fund for the Doctoral Program of Higher Education of China under Grant 20130182120017, and by the Innovative Talent of Colleges and University of Henan Province under grant 18HASTIT021.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/LCOMM.2019.2907490, IEEE Communications Letters



density function (CDF) of $g_{SD}$ are [12]

$$f_{g_{SD}}(x) = \frac{G_{0,2}^{2,0}\left(\frac{k_d m_d x}{\mu_d}\left|_{k_d,m_d}^{-}\right.\right)}{\Gamma(k_d)\Gamma(m_d)x}, \quad (3)$$

$$F_{g_{SD}}(x) = \frac{G_{1,3}^{2,1}\left(\frac{k_d m_d x}{\mu_d}\left|_{k_d,m_d,0}^{1}\right.\right)}{\Gamma(k_d)\Gamma(m_d)}, \quad (4)$$

respectively, where $\mu_d$ is the average of $g_{SD}$, and $m_d, k_d$ are parameters of GK fading. $G_{:,:}^{:,:}(\cdot)$ and $\Gamma(\cdot)$ denote the Meijer-G and Gamma functions [15], respectively. To avoid Meijer-G function in the final SOP expression, we adopt the approximate PDF proposed by [11], [13],

$$f_{g_{SD}}(x) = \sum_{j_d=1}^{L} a_{d,j_d} x^{m_d-1}\exp(-\zeta_{d,j_d}x), \quad (5)$$

where $a_{d,j_d} = \frac{\theta_{d,j_d}}{\sum_{n=1}^{L}\theta_{d,n}\Gamma(m_d)\zeta_{d,n}^{-m_d}}$, $\zeta_{d,j_d} = \frac{k_d m_d}{\mu_d t_{j_d}}$, $\theta_{d,j_d} = \left(\frac{k_d m_d}{\mu_d t_{j_d}}\right)^{m_d}\frac{\omega_{j_d} t_{j_d}^{k_d-m_d-1}}{\Gamma(m_d)\Gamma(k_d)}$, $\omega_{j_d}$, $t_{j_d}$ and $L$ are the weight factor, the abscissas, and summation terms for the Gaussian-Laguerre integration.

We can also get the PDFs of $g_{SE}, g_{BS}$ in similar forms to (5), where the definition of $\mu_t, m_t, k_t, a_{t,j_t}, \zeta_{t,j_t}$, $t \in \{e, s\}$, is similar to that of $\mu_d, m_d, k_d, a_{d,j_d}, \zeta_{d,j_d}$, respectively.

## III. Secrecy Outage Probability

If the transmitter knows the channel state information (CSI) of the wiretap channel, the transmitter can adjust the rate of confidential information ($R_s$) without exceeding the instantaneous secrecy capacity ($C_s$) according to the instantaneous CSI of the wiretap channel to achieve the perfect security, where $C_s$ is defined as $C_s = \max\{C_d - C_e, 0\}$, where $C_d = \log_2(1+\gamma_D)$ and $C_e = \log_2(1+\gamma_E)$ denote the channel capacity of the main channel and wiretap channel, respectively.

We assume that $S$ only knows the CSI of $S-D$ link, and does not have access to the CSI of $S-E$ link, i.e., silent eavesdropping. In this case, there exists a secrecy outage, because of the constant $R_s$. Here, we adopt the definition of SOP in [3]

$$\begin{aligned}\text{SOP} &= \Pr\{\log_2(1+\gamma_D) - \log_2(1+\gamma_E) \le R_s\} \\ &= \Pr\{\gamma_D \le \lambda - 1 + \lambda\gamma_E\} \\ &= \int_0^\infty\int_0^{\lambda-1+\lambda y} f_{\gamma_D,\gamma_E}(x,y)\,dxdy, \quad (6)\end{aligned}$$

where $f_{\gamma_D,\gamma_E}(\cdot,\cdot)$ is the joint PDF of $\gamma_D$ and $\gamma_E$, and $\lambda = 2^{R_s}$.

After some mathematical manipulations, the approximate joint PDF of $\gamma_D$ and $\gamma_E$ can be derived as

$$f_{\gamma_D,\gamma_E}(x,y) \approx \sum_{j_d=1}^{L} a_{d,j_d}\sum_{j_e=1}^{L} a_{e,j_e}\sum_{j_s=1}^{L} a_{s,j_s}\zeta_{s,j_s}^{m}\sum_{i=1}^{L}\omega_i\frac{t_i^{-m-1}}{\alpha^2} \left(\frac{x}{\alpha}\right)^{m_d-1}\left(\frac{y}{\alpha}\right)^{m_e-1}\exp\left(-\frac{\zeta_{d,j_d}\zeta_{s,j_s}x}{\alpha t_i}\right)\exp\left(-\frac{\zeta_{e,j_e}\zeta_{s,j_s}y}{\alpha t_i}\right), \quad (7)$$

where $\omega_i$ and $t_i$ represent the weight factor and abscissas of the Gaussian-Laguerre integration, respectively.

From $\int_0^\infty\int_0^\infty f_{\gamma_D,\gamma_E}(\gamma_D,\gamma_E)d\gamma_D d\gamma_E = 1$, we have $\frac{1}{\Gamma(m_s)}\sum_{i=1}^{L}\omega_i t_i^{m_s-1} = 1$, which can be used to simplify our following expressions.

By using some mathematical manipulations, SOP can be finally derived as

$$\begin{aligned}\text{SOP} =& 1 - \sum_{j_d=1}^{L}\sum_{j_e=1}^{L}\sum_{j_s=1}^{L}\sum_{i=1}^{L}\omega_i a_{s,j_s}a_{e,j_e}a_{d,j_d}(m_d-1)! \\ &\sum_{k=0}^{m_d-1}\frac{1}{k!}\sum_{n=0}^{k}\binom{k}{n}(\lambda-1)^{k-n}\lambda^n\frac{(m_e+n-1)!}{(\zeta_{e,j_e}+\zeta_{d,j_d}\lambda)^{m_e+n}} \\ &\zeta_{s,j_s}^{-m_s+k-n}\zeta_{d,j_d}^{-m_d+k}t_i^{m_s-1-k+n}\alpha^{-k+n} \\ &\exp\left(-\frac{\zeta_{d,j_d}\zeta_{s,j_s}(\lambda-1)}{\alpha t_i}\right). \quad (8)\end{aligned}$$

Although the closed-form expression for SOP includes many summation terms, there are only elementary functions, which is easier to calculate and analyze, compared to Meijer-G and other special functions. Moreover, there is a debate about whether the Meijer-G function is a closed-form outcome, especially in the engineering field [10].

### A. Special Cases

The expression for SOP is complicated and not easy to get some insights. In the following, we will present some simplified expressions for SOP in some special cases.

When $\alpha \to \infty$, SOP becomes

$$\begin{aligned}\text{SOP} =& 1 - \sum_{j_d=1}^{L}\sum_{j_e=1}^{L} a_{e,j_e}a_{d,j_d}(m_d-1)! \\ &\sum_{k=0}^{m_d-1}\frac{\lambda^k(m_e+k-1)!}{k!(\zeta_{e,j_e}+\zeta_{d,j_d}\lambda)^{m_e+k}}\zeta_{d,j_d}^{-m_d+k}, \quad (9)\end{aligned}$$

which shows that there is no impact of $B-S$ link on SOP as $\alpha \to \infty$.

When $m_d = m_e = m_s = 1$, i.e., Log-normal-Rayleigh composite fading, SOP becomes

$$\begin{aligned}\text{SOP} =& 1 - \sum_{j_d=1}^{L}\sum_{j_e=1}^{L}\sum_{j_s=1}^{L}\sum_{i=1}^{L}\omega_i a_{s,j_s}a_{e,j_e}a_{d,j_d} \\ &\frac{\exp\left(-\frac{\zeta_{s,j_s}\zeta_{d,j_d}(\lambda-1)}{\alpha t_i}\right)}{(\zeta_{e,j_e}+\zeta_{d,j_d}\lambda)\zeta_{s,j_s}\zeta_{d,j_d}}. \quad (10)\end{aligned}$$

It is easy to see that SOP is a decreasing function with respect to $\alpha$. If we want to make SOP lower, $\alpha$ should be larger, i.e., increasing the transmit power at $B$ or the ratio of $T_1$ to $T_2$. In real communications systems, there normally exits a maximal transmit power constraint at $B$, and thus, improving the transmit power at $B$ may not be always an effective way to achieve a lower SOP. The increase in the ratio of $T_1$ to $T_2$ can alternatively achieve a lower SOP, instead of enhancing the transmit power at $B$. However, when $\alpha$ is large sufficiently, larger $\alpha$ will not achieve a much better SOP, because of the lower bound in (9).

The probability of non-zero secrecy capacity (PNSC) is another important secrecy performance metric, which can be

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easily derived by using the expression for SOP,

$$\begin{aligned}\mathrm{PNSC} &= \Pr\{C_s > 0\} = 1 - \mathrm{SOP}|_{R_s=0} \\ &= \sum_{j_d=1}^{L}\sum_{j_e=1}^{L} a_{e,j_e} a_{d,j_d}\,(m_d-1)! \\ &\quad \sum_{k=0}^{m_d-1}\frac{1}{k!}\frac{(m_e+k-1)!\,\zeta_{d,j_d}^{-m_d+k}}{(\zeta_{e,j_e}+\zeta_{d,j_d})^{m_e+k}},\end{aligned} \tag{11}$$

where the impact of $B-S$ link vanishes.

### B. Effective Secrecy Throughput

Due to the fact that the CSI of $S-D$ link is available at $S$, $S$ can adopt the maximal code rate (i.e., $C_d$) for the signal transmission to $D$, which is denoted as adaptive transmission scheme in the Subsection III-A of [16]. In this adaptive transmission scheme, the EST is defined as [16]

$$\begin{aligned}\Psi(R_e) &= (C_d - R_e)\Pr\left\{\gamma_e < 2^{R_e}-1\right\} \\ &= (C_d - R_e)\,F_{g_{SE}}\left(\frac{g_{SD}}{\lambda}\right),\end{aligned} \tag{12}$$

where $\lambda = 2^{R_s}$, $F_{g_{SE}}(\cdot)$ denotes the CDF of $g_{SE}$, and the redundancy rate $R_e = C_d - R_s$ is used to secure message transmission against eavesdropping.

## IV. Asymptotic Analysis

The asymptotic behaviour over GK fading channels is normally complicated [14], because the diversity order of SOP in high SNRs in this work depends on $k_d$, $m_d$, $k_s$ and $m_s$, and the asymptotic CDF for $\gamma_D$ is not a line function with respect to $\log(\mu_d)$ for $k_d = m_d$ or $k_s = m_s$.

Here, we only consider a special case where the diversity order of $S-D$ link is less than that of $B-S$ link, i.e., $\min\{k_d, m_d\} < \min\{k_s, m_s\}$. When the average channel power gain of $S-D$ link ($\mu_d$) approaches infinity, i.e., $\zeta_{d,j_d} \to 0$, the asymptotic PDF of $g_{SD}$ is[1] [14]

$$f_{g_{SD}}^{\infty}(x) = \underbrace{\frac{\Gamma(|k_d-m_d|)\,(k_d m_d)^{v_d}}{\Gamma(k_d)\,\Gamma(m_d)}}_{\Delta}\frac{x^{v_d-1}}{\mu_d^{v_d}} = \frac{\Delta x^{v_d-1}}{\mu_d^{v_d}}, \tag{13}$$

where $v_d = \min\{k_d, m_d\}$, and $k_d \neq m_d$.

The corresponding joint PDF of $\gamma_D$ and $\gamma_E$ becomes

$$\begin{aligned}f_{\gamma_D,\gamma_E}(x,y) &= \frac{\Delta}{\mu_d^{v_d}}\sum_{j_e=1}^{L} a_{e,j_e}\sum_{j_s=1}^{L} a_{s,j_s}\left(\frac{x}{\alpha}\right)^{v_d-1}\left(\frac{y}{\alpha}\right)^{m_e-1} \\ &\frac{2}{\alpha^2}\left(\frac{\zeta_{e,j_e} y}{\alpha\zeta_{s,j_s}}\right)^{\frac{-v_d-m_e+m_s}{2}} K_{-v_d-m_e+m_s}\left(2\sqrt{\frac{\zeta_{s,j_s}\zeta_{e,j_e} y}{\alpha}}\right),\end{aligned} \tag{14}$$

where $K_{\cdot}(\cdot)$ denotes the second modified bessel function [15].

By substituting the joint PDF into the SOP definition, SOP becomes (16), shown on the top of next page, where the integral can be derived in closed-form for $m_s > v_d$. When $m_s > v_d$, the asymptotic SOP (ASOP) in high SNRs can be derived as (17), shown on the top of next page, which shows that the diversity order is $v_d$.

Due to the page limitation, we only give some comments for ASOP in the general case. When $v_d > v_s$, where $v_s = \min\{k_s, m_s\}$, the diversity order of ASOP is $v_s$. When $v_d > v_s$ and $k_s = m_s$ (or $v_d < v_s$ and $k_d = m_d$), the ASOP is not a line function with respect to $\log(\mu_d)$, although the diversity order is still $v_s$ (or $v_d$). To summarize, the diversity order ($O$) of ASOP is

$$O = \begin{cases} v_d, & v_d \le v_s; \\ v_s, & v_d > v_s. \end{cases} \tag{15}$$

This conclusion for the diversity order is also valid over Nakagami-$m$ fading channels (no shadowing).

## V. Numerical Results

Fig. 1 plots SOP versus $\mu_d$ for different $k_d$ and $m_d$, where the decreasing trend of SOP is presented with $\mu_d$ ($m_d$ or $k_d$) increasing, due to the improved $S-D$ link. This decreasing trend of SOP is also obvious in Fig. 2 as $\mu_e$ decreases, due to the worse $S-E$ link. The difference of the diversity order for different $k_d$ and $m_d$ is shown in the different slope in Figs. 1-2, where we only consider the case of $v_d < v_s$.

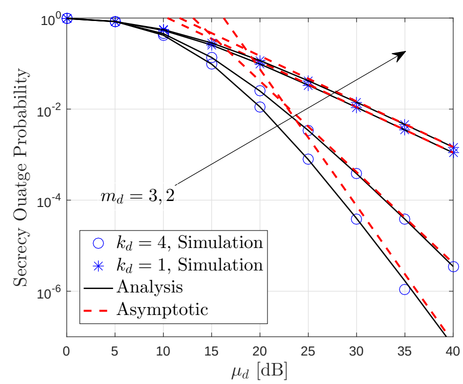


Fig. 1. SOP versus $\mu_d$ for $\mu_s = \mu_e = 1$, $k_e = k_s = 4$, $m_e = m_s = 4$, $P_B = 5$ dB, $T_1 = 1$, $T_2 = 2$, and $R_s = 2$.

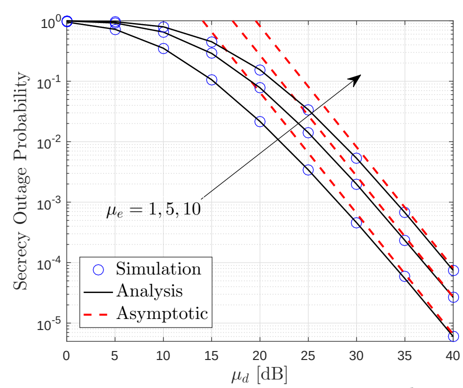


Fig. 2. SOP versus $\mu_d$ for $m_d = 2$, $m_e = m_s = 4$, $k_d = k_e = k_s = 3$, $P_B = 1$ dB, $T_1 = 1$, $T_2 = 2$, $\mu_s = 1$, and $R_s = 1$.

As presented in Fig. 3, we can see that SOP is in decline with $\alpha$ increasing, because the transmit power at $B$ (or the ratio of $T_1$ to $T_2$) increases, resulting in the improved transmit power at $S$. However, when $\alpha$ is large sufficiently, there is no obvious improvement in SOP for a larger $\alpha$, which means that the impact of $B-S$ link vanishes. The lower bound for SOP is smaller when the number of multi-path clusters becomes larger.

[1] There is no asymptotic expression for $m_d = k_d$ [14], because the asymptotic CDF of $g_{SD}$ is not a line function with respect to $\log(\mu_d)$, although the diversity order is still $v_d$.

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$$\mathrm{SOP}^{\infty}=\frac{\Delta}{\mu_d^{v_d}}\sum_{j_e=1}^{L}a_{e,j_e}\sum_{j_s=1}^{L}a_{s,j_s}\frac{2}{\alpha^{\frac{v_d+m_e+m_s}{2}}}\frac{1}{v_d}\left(\frac{\zeta_{e,j_e}}{\zeta_{s,j_s}}\right)^{\frac{-v_d-m_e+m_s}{2}}\int_0^{\infty}y^{\frac{-v_d+m_e+m_s}{2}-1}(\lambda-1+\lambda y)^{v_d}K_{-v_d-m_e+m_s}\left(2\sqrt{\frac{\zeta_{s,j_s}\zeta_{e,j_e}y}{\alpha}}\right)dy. \tag{16}$$

$$\mathrm{SOP}^{\infty}=\left\{\Delta\sum_{j_e=1}^{L}a_{e,j_e}\sum_{j_s=1}^{L}a_{s,j_s}\frac{\zeta_{e,j_e}^{-m_e}\zeta_{s,j_s}^{v_d-m_s}}{\alpha^{v_d}v_d}\sum_{n=0}^{v_d}\binom{v_d}{n}(\lambda-1)^{v_d-n}\lambda^n\left(\frac{\alpha}{\zeta_{s,j_s}\zeta_{e,j_e}}\right)^n\Gamma\left(m_e+n\right)\Gamma\left(m_s-v_d+n\right)\right\}\mu_d^{-v_d}. \tag{17}$$

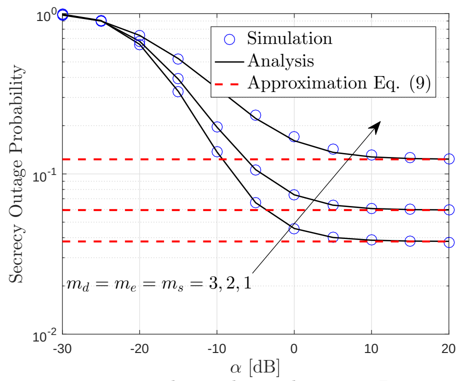


Fig. 3. SOP versus $\alpha$ for $k_d = k_e = k_s = 3$, $P_B = 1$ dB, $T_1 = 1$, $\mu_d = 10$, $\mu_e = \mu_s = 1$, and $R_s = 0.1$.

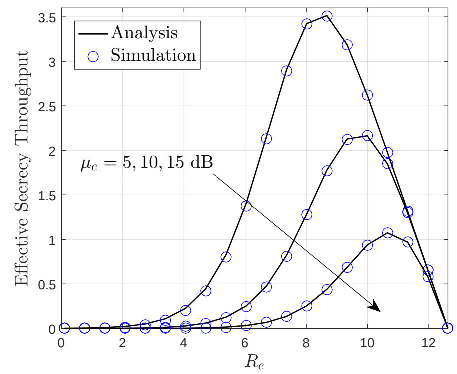


Fig. 5. EST versus $R_e$ for $m_d = m_e = m_s = 2$, $k_d = k_e = k_s = 4$, $P_B = 10$ dB, $T_1 = 2$, $T_2 = 1$, $g_{SD} = 20$ dB, and $g_{BS} = 5$ dB.

The increasing trend of PNSC is shown in Fig. 4 as $\mu_d$ increases, because of the improved main link. In the low $\mu_d$ region, PNSC is reduced as $k_d = k_e = k_s$ increases, although the shadowing becomes lighter.

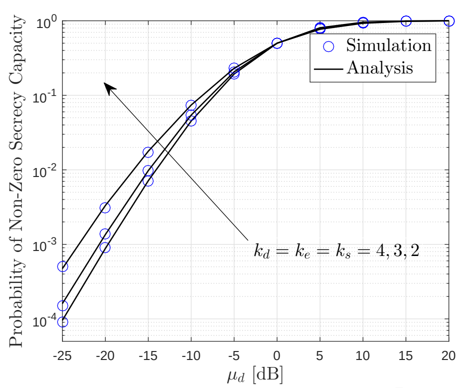


Fig. 4. PNSC versus $\mu_d$ for $m_d = m_e = m_s = 2$, $P_B = 5$ dB, $T_1 = 1$, $T_2 = 2$, $\mu_e = \mu_s = 1$, and $R_s = 1$.

As shown in Fig. 5, when $R_e$ changes, there is a locally maximum point for EST, which becomes large for a large $\mu_e$. It is also obvious that EST is a decreasing function with respect to $\mu_e$, due to the improved wiretap channel.

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