On Secrecy Outage of MISO SWIPT Systems in the Presence of Imperfect CSI

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***Abstract*—In this work, a multiple-input single-output (MISO) simultaneous wireless information and power transfer (SWIPT) system including one base station (BS) equipped with multiple antennas, one desired single-antenna information receiver (IR) and N ($N > 1$) single-antenna energy-harvesting receivers (ERs) is considered. By considering that the information signal of the desired IR may be eavesdropped by ERs if ERs are malicious, we investigate the secrecy performance of the target MISO SWIPT system when imperfect channel state information (CSI) is available and adopted for transmit antenna selection at the BS. Considering that each eavesdropping link experiences independent not necessarily identically distributed Rayleigh fading, the closed-form expressions for the exact and the asymptotic secrecy outage probability are derived and verified by simulation results.**

***Index Terms*—Simultaneous wireless information and power transfer, secrecy outage probability, multiple-input single-output, channel state information.**

I. Introduction

As a green and convenient energy harvesting (EH) solution to energy-constrained systems, simultaneous wireless information and power transfer (SWIPT) has gained a great deal of attention, which adopts the same emitted electromagnetic wave to transport both energy that can be harvested at the receiver, and information that is decoded by the receiver [1].

Initial research works in the field of SWIPT focused on single-input-single-output (SISO) systems [1]-[2]. Motivated by benefits of multi-antenna techniques, multiple-input single-output (MISO) and multiple-input-multiple-output (MIMO) SWIPT systems have drawn considerable attention in [2]-[3] and [4]-[5], respectively. However, these aforementioned works were carried on while assuming that the perfect channel state information (CSI) was available. However, in practice, it is difficult to obtain perfect CSI because of channel estimation and quantization errors. Specially, in fact, the energy receivers (ERs) are not continuously interacting with the transmitter and the corresponding CSI at the transmitter may be outdated even if the channel is only slowly time varying.

Recently, some works have studied MISO and MIMO SWIPT systems while considering imperfect CSI in [6]-[7] and [8]-[9], respectively. Clearly, these aforementioned investigations [2]-[9] were mainly presented on power control, transmission strategy and resource scheduling to optimize the performance SWIPT systems. Some of them, like [3], [5]-[7] and [9], studied the secrecy transmission in SWIPT while considering perfect/imperfect CSI.

In SWIPT systems, an energy signal is transmitted along with the information signal to expedite EH at the ERs. In practice, the transmitter could increase the transmitting power of the information carrying signal to facilitate EH at the ERs. However, this may also lead to an increased susceptibility to eavesdropping due to a higher potential for information leakage when ERs are malicious. Therefore, a new quality of service concern on communication security arises in SWIPT systems, which is very important to tackle. In [12], the secrecy performance (secrecy outage and secrecy capacity) has been studied for single-input multiple-output SWIPT systems. To the best of authors knowledge, there have been no previous results reported on the secrecy performance analysis for SWIPT systems in the presence of imperfect CSI.

In this paper, a MISO SWIPT system consisting of one BS equipped with multiple antennas, one desired IR and N ($N > 1$) ERs is considered. In particular, we focus on secrecy outage probability (SOP) in the presence of eavesdroppers (ERs), and derive the closed-form analytical expression for the exact and the asymptotic secrecy outage probability while considering imperfect CSI and each eavesdropping link experiences independent not necessarily identically Rayleigh fading.

II. System model

In this paper, we consider a MISO downlink SWIPT system consisting of one BS equipped with N_T ($N_T > 1$) antennas, one desired IR and N ($N > 1$) ERs, denoted by $\mathrm{ER}_1, \cdots, \mathrm{ER}_N$, respectively, over a given frequency band, which are with a single antenna, as shown in Fig. 1. It is assumed that all links between each antenna of the BS and IR experience independent and identically Rayleigh fading with same and all links between each antenna of the BS and ERs experience independent not necessarily identically Rayleigh fading.

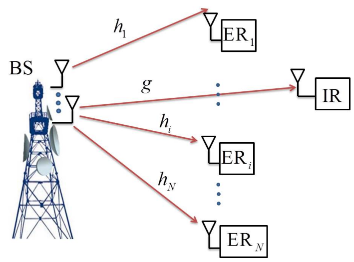

Fig. 1. System model

We assume that IR feedbacks the CSI to BS and that there is no CSI feedback from ERs to BS (i.e., at this time ERs may play as passive eavesdroppers). The CSI feedback from IR is delayed and BS encodes the message to Bob by using IR's outdated CSI to select a single transmit antenna which yields the maximum instantaneous SNR. Thus, the largest channel gain of the links between the selected antenna at BS and IR at the selection instant can be expressed as $\tilde{g} = \max_{k \in \{1,\cdots,N_T\}} \{\tilde{g}_k\}$, where $\tilde{g}_k$ is the delayed channel coefficient between BS's kth antenna and IR, which is different from the actual channel coefficient between BS's kth antenna and IR, g_k.

After the antenna selection, BS deliveries information to IR and transfers energy to all ERs simultaneously. All EH receivers are supposed to harvest energy from the RF. However, the signals intended for the desired IR may be overheard and eavesdropped by all ERs since all EH receivers are malicious and in the coverage range. Hence, all ERs are potential eavesdroppers which should be considered. In this work, we assume that all ERs work independently and no information exchange exists among these ERs.

It is also assumed that each ER adopts power splitting (PS) method to coordinate the processes of information decoding and EH from the received signal [4]. Specifically, as shown in Fig. 2 in [12], the received signal at each EH is split to the information decoding (ID) and the EH by a power splitter, which divides an ρ_i $(0 \le \rho_i \le 1)$ portion of the signal power to the ID, and the remaining $1-\rho_i$ portion of power to the EH.

Then, the received signal in the downlink is given by $y_{\mathrm{IR}} = \sqrt{P_t} g s + n_{\mathrm{IR}}$ and $y_{\mathrm{EH}i} = \sqrt{\rho_i}\left(\sqrt{P_t} h_i s + n_{\mathrm{EH}i}\right) + z_i$, respectively, where P_t is the transmitting power at BS, g is the channel gain of the link between the selected transmit antenna at BS and IR, s denotes the transmitted symbols from BS, h_i is the link channel gain between the selected transmit antenna at BS and the ith EH receiver, n_{IR} and $n_{\mathrm{EH}i}$ denote the independent complex Gaussian noise at the desired IR and the ith EH receiver, respectively. In this work, to simplify the analysis, we assume that n_{IR} and $n_{\mathrm{EH}i}$ are with zero means and a same variances, N_0, z_i is the signal processing noise by the ID at the ith EH, which can also be modeled as additional white Gaussian noise with zero means and variances σ_i^2. The correlation relationship between $\tilde{g}_k$ and g_k can be modeled as $\tilde{g}_k = \sqrt{\eta} g_k + \sqrt{1-\eta}\,\omega_k$, where ω_k represents a complex Gaussian variable with zero mean and variance $\sigma^2_{\mathrm{IR}_k}$, where $\sigma^2_{\mathrm{IR}_k}$ is the variance of g_k, η is given by $\eta = [J_0(2\pi f_d \tau)]^2$, where $J_0(\cdot)$ denotes the 0th order Bessel function of first kind as defined by Eq. (8.402) in [14] and f_d indicates the maximum Doppler frequency.

The SNR of the signal at IR and the ID at EH$_{\mathrm{i}}$ can be written as $\gamma_g = \frac{P_t |g|^2}{N_0}$ and $\gamma_{\mathrm{EH}i} = \frac{\rho_i P_t |h_i|^2}{\rho_i N_0 + \sigma_i^2}$, respectively. Thus, the instantaneous secrecy capacity can be presented as

$$C_s(\gamma_g, \gamma_{\max}) = \left[\log_2(1+\gamma_g) - \log_2(1+\gamma_{\max})\right]^+, \quad (1)$$

where $[x]^+$ denotes $\max\{x, 0\}$, $\gamma_{\max} = \max_{i\in\{1,\cdots,N\}} \{\gamma_{\mathrm{EH}i}\}$.

The probability density function (PDF) of $|\tilde{g}_k|^2$ and $|h_i|^2$ can be given as $f_{|\tilde{g}_k|^2}(x) = \frac{1}{g_{\mathrm{A}}}\exp\left(-\frac{x}{g_{\mathrm{A}}}\right)$ and $f_{|h_i|^2}(x) = \frac{1}{h_{\mathrm{A}i}}\exp\left(-\frac{x}{h_{\mathrm{A}i}}\right)$, respectively, where g_{A} and $h_{\mathrm{A}i}$ are the expectation of channel power gain $|\tilde{g}_k|^2$ and $|h_i|^2$, respectively.

Then, we can obtain $\gamma_{\tilde{g}_k} = \frac{P_t}{N_0}|\tilde{g}_k|^2 \sim \mathrm{Exp}(\lambda_A)$ and $\gamma_{\mathrm{EH}i} \sim \mathrm{Exp}(\lambda_{\mathrm{EH}i})$, where $\lambda_A = \frac{N_0}{g_{\mathrm{A}} P_t}$ and $\lambda_{\mathrm{EH}i} = \frac{\rho_i N_0 + \sigma_i^2}{h_{\mathrm{A}i}\rho_i P_t}$. Further, it is easy to obtain the PDF of $\gamma_{\max}$ as

$$f_{\gamma_{\max}}(x) = \sum_{i=1}^{N} \lambda_{\mathrm{EH}i}\exp(-\lambda_{\mathrm{EH}i}x) \prod_{\substack{j=1\\ j\neq i}}^{N} \left[1-\exp(-\lambda_{\mathrm{EH}j}x)\right]. \quad (2)$$

The PDF of $\gamma_{\tilde{g}} = \frac{P_t L_c |\tilde{g}|^2}{N_0 d_{\mathrm{B,I}}{}^{\kappa}}$ can be written as

$$f_{\gamma_{\tilde{g}}}(x) = N_T \left[F_{\gamma_{\tilde{g}_k}}(x)\right]^{N_T-1} f_{\gamma_{\tilde{g}_k}}(x), \quad (3)$$

where $F_{\gamma_{\tilde{g}_k}}(x)$ is the cumulative distribution function of $\gamma_{\tilde{g}_k}$.

As all links between each antenna at the BS and IR experience independent and identically Rayleigh fading, the PDF of γ_g can be obtained as

$$f_{\gamma_g}(x) = \int_0^{\infty} f_{\gamma_g|\gamma_{\tilde{g}}}(x|y) f_{\gamma_{\tilde{g}}}(y)\, dy, \quad (4)$$

where $f_{\tilde{\gamma}_g|\gamma_g}(x|y)$ is the joint PDF of γ_g and $\gamma_{\tilde{g}}$ (for a correlation coefficient η) is given by [13]

$$f_{\gamma_g|\gamma_{\tilde{g}}}(x|y) = \frac{\lambda_A}{1-\eta}\exp\left(-\lambda_A\frac{x+\eta y}{1-\eta}\right)\cdot I_0\left(\frac{2\lambda_A\sqrt{\eta x y}}{1-\eta}\right), \quad (5)$$

where $I_0(\cdot)$ is the 0th order modified Bessel function of first kind as defined by Eq. (8.406) in [14].

Then, substituting (3) and (5) into (4), the PDF of γ_g can be

$$f_{\gamma_g}(x) = \frac{N_T(\lambda_A)^2}{1-\eta}\exp\left(-\frac{\lambda_A}{1-\eta}x\right)\sum_{i=0}^{N_T-1}\binom{N_T-1}{i}(-1)^i \cdot \int_0^{\infty}\exp\left(-\lambda_A\left(\frac{1}{1-\eta}+i\right)y\right)\cdot I_0\left(\frac{2\lambda_A\sqrt{\eta x y}}{1-\eta}\right)dy. \quad (6)$$

Let $z = \sqrt{y}$, $dy = 2zdz$. Then, by using Eq. (2.15.5.4) in [15], the integral in last equation can be written as

$$\int_0^{\infty}\exp\left(-\lambda_A\left(\frac{1}{1-\eta}+i\right)y\right)\cdot I_0\left(\frac{2\lambda_A\sqrt{\eta x y}}{1-\eta}\right)dy$$

$$= {\lambda_A}^{-1}\left(\frac{1}{1-\eta}+i\right)^{-1}\exp\left(\frac{\eta\left(\frac{\lambda_A}{1-\eta}\right)^2 x}{\lambda_A\left(\frac{1}{1-\eta}+i\right)}\right) \quad . \tag{7}$$

Substituting (7) into (6), we obtain

$$f_{\gamma_g}(x) = N_T \sum_{i=0}^{N_T-1}\binom{N_T-1}{i}(-1)^i A_i \exp(-B_i x), \tag{8}$$

where $A_i = \frac{\lambda_A}{1+(1-\eta)i}$ and $B_i = A_i(i+1)$.

III. Secrecy outage analysis

In this paper, SOP is defined as the probability that instantaneous secrecy capacity is below a threshold secrecy rate, C_{th} ($C_{th} \geq 0$). Then, SOP can be written as

$$SOP\,(C_{th}) = \Pr\{C_s \leq C_{th}\} = \Pr\left\{\frac{1+\gamma_g}{1+\gamma_{\max}} \leq 2^{C_{th}}\right\}$$
$$= \Pr\{\gamma_g \leq \alpha\,(1+\gamma_{\max}) - 1\}, \tag{9}$$

where $\alpha = 2^{C_{th}}$.

For simplification, let $\lambda_i = \lambda_{\mathrm{EH}i}$ in the rest of the paper. Then, we can rewrite (2) as

$$f_{\gamma_{\max}}(x) = \sum_{i=1}^{N}\lambda_i \exp(-\lambda_i x)\prod_{\substack{j=1\\ j\neq i}}^{N}[1-\exp(-\lambda_j x)]. \tag{10}$$

Further, we can obtain [12]

$$\prod_{\substack{j=1\\ j\neq i}}^{N}[1-\exp(-\lambda_j x)] = \sum_{p=0}^{N-1}(-1)^p \cdot \sum\nolimits_{m=1}^{\binom{|\Omega_{N,i}|}{p}}$$
$$\cdot\exp\left(-\boldsymbol{\lambda}_{p,m}^T \mathbf{I}_p x\right) = \sum\nolimits_p\sum\nolimits_m \exp\left(-\boldsymbol{\lambda}_{p,m}^T \mathbf{I}_p x\right), \tag{11}$$

where $\Omega_{N,i} = \{\lambda_1, \lambda_2, \cdots, \lambda_N\} - \{\lambda_i\}$, $|\Omega_{N,i}|$ denotes the number of the elements in $\Omega_{N,i}$, $(\cdot)^T$ denotes the transpose operator, $\boldsymbol{\lambda}_{p,m}$ is the vector of $\Omega_{N,i,m,p}\cup\{0\}$, $\Omega_{N,i,m,p}$ is the mth ($1 \leq m \leq \binom{|\Omega_{N,i}|}{p}$) subset with p elements of $\Omega_{N,i}$, $\mathbf{I}_p$ is the unit vector with $(1+p)$ elements. In the following, we use $\sum_p\sum_m$ instead of $\sum\limits_{p=0}^{N-1}(-1)^p\cdot\sum_{m=1}^{\binom{|\Omega_{N,i}|}{p}}$ for simplification.

Then, making use of (11), (10) can be written as

$$f_{\gamma_{\max}}(x) = \sum_{i=1}^{N}\lambda_i\exp(-\lambda_i x)\sum\nolimits_p\sum\nolimits_m\exp\left(-\boldsymbol{\lambda}_{p,m}^T\mathbf{I}_p x\right)$$
$$= \sum_{i=1}^{N}\lambda_i\sum\nolimits_p\sum\nolimits_m\exp(-\Theta_i x), \tag{12}$$

where $\Theta_i = \boldsymbol{\lambda}_{p,m}^T\mathbf{I}_p + \lambda_i$.

Therefore, we can obtain

$$SOP\,(C_{th}) = \int_0^\infty\int_0^{\alpha(1+y)-1} f_{\gamma_g}(x)\,f_{\gamma_{\max}}(y)\,dxdy$$
$$= N_T\sum_{i=0}^{N_T-1}\binom{N_T-1}{i}\frac{(-1)^i A_i}{B_i}$$
$$\cdot\int_0^\infty f_{\gamma_{\max}}(y)\,[1-\exp(-B_i\alpha y - B_i\alpha + B_i)]dy$$
$$= I_1 + I_2, \tag{13}$$

where $I_1 = N_T\sum\limits_{i=0}^{N_T-1}\binom{N_T-1}{i}\frac{(-1)^i A_i}{B_i}\int\limits_0^\infty f_{\gamma_{\max}}(y)dy$ and $I_2 = -N_T\sum\limits_{i=0}^{N_T-1}\binom{N_T-1}{i}\frac{(-1)^i A_i}{B_i}\exp(-B_i\alpha + B_i)\cdot\int\limits_0^\infty f_{\gamma_{\max}}(y)\exp(-B_i\alpha y)dy$.

Making use of (12), we can rewrite I_1 and I_2 as

$$I_1 = N_T\sum_{i=0}^{N_T-1}\binom{N_T-1}{i}\frac{(-1)^i A_i}{B_i}\sum_{j=1}^{N}\lambda_j\sum\nolimits_p\sum\nolimits_m\frac{1}{\Theta_j}, \tag{14}$$

$$I_2 = -N_T\sum_{i=0}^{N_T-1}\binom{N_T-1}{i}\frac{(-1)^i A_i}{B_i}\exp(-B_i\alpha + B_i)$$
$$\cdot\sum_{j=1}^{N}\lambda_j\sum\nolimits_p\sum\nolimits_m\frac{1}{\Theta_j + B_i\alpha}, \tag{15}$$

respectively.

Thus, SOP can be obtained by substituting (14) and (15) into (13).

In the following, we will derive the asymptotic SOP while $\bar{\gamma}_A = \frac{P_t g_A L_c}{N_0 {d_{\mathrm{B,I}}}^{\eta}} \to \infty$ (namely, $\bar{\gamma}_A = {\lambda_A}^{-1} \to \infty$). Then, we can rewrite (15) as

$$f_{\gamma_g}(x) = \frac{N_T}{\bar{\gamma}_A}\sum_{i=0}^{N_T-1}\binom{N_T-1}{i}\frac{(-1)^i}{A_i'}\exp\left(-\frac{B_i'}{\bar{\gamma}_A}x\right), \tag{16}$$

where $A_i' = 1 + (1-\eta)i$ and $B_i' = \frac{i+1}{1+(1-\eta)i}$.

Using the Taylor series expansion of the exponential function in (16) given by $\exp\left(-\frac{B_i'}{\bar{\gamma}_A}x\right) = \sum\limits_{l=0}^{\infty}\frac{\left(-\frac{B_i'}{\bar{\gamma}_A}x\right)^l}{l!}$ and only keeping the first two terms while neglecting the higher order terms, we can rewrite SOP in (13) as

$$SOP\,(C_{th}) = \frac{N_T}{\bar{\gamma}_A}\sum_{i=0}^{N_T-1}\binom{N_T-1}{i}\frac{(-1)^i}{\mathrm{A}_i'}$$
$$\cdot\int_0^\infty f_{\gamma_{\max}}(y)\left(C_1 y^2 + C_2 y + C_3\right)dy$$
$$= D_1 + D_2 + D_3, \tag{17}$$

where $C_1 = -\frac{B_i'}{2\bar{\gamma}_A}\alpha^2$, $C_2 = \alpha\left(1 + \frac{B_i'}{\bar{\gamma}_A} - \frac{B_i'}{\bar{\gamma}_A}\alpha\right)$, $C_3 = \alpha - 1 - \left(1 - 2\alpha + \alpha^2\right)\frac{B_i'}{2\bar{\gamma}_A}$, $D_1 = \frac{N_T}{\bar{\gamma}_A}\sum\limits_{i=0}^{N_T-1}\left(\begin{array}{c} N_T - 1 \\ i \end{array}\right)\frac{(-1)^i C_1}{\mathrm{A}_i'}\int\limits_0^\infty f_{\gamma_{\max}}(y)\, y^2 dy$,
$D_2 = \frac{N_T}{\bar{\gamma}_A}\sum\limits_{i=0}^{N_T-1}\left(\begin{array}{c} N_T - 1 \\ i \end{array}\right)\frac{(-1)^i C_2}{\mathrm{A}_i'}\int\limits_0^\infty f_{\gamma_{\max}}(y)\, y dy$,
and $D_3 = \frac{N_T}{\bar{\gamma}_A}\sum\limits_{i=0}^{N_T-1}\left(\begin{array}{c} N_T - 1 \\ i \end{array}\right)\frac{(-1)^i C_3}{\mathrm{A}_i'}\int\limits_0^\infty f_{\gamma_{\max}}(y) dy$.

Making use of (12) and Eq. (3.351.3) in [14], we can rewrite D_1, D_2 and D_3 as

$$D_1 = \frac{2N_T}{\bar{\gamma}_A}\sum_{i=0}^{N_T-1}\left(\begin{array}{c} N_T - 1 \\ i \end{array}\right)\frac{(-1)^i \mathrm{E}_1}{\mathrm{A}_i'}\sum_{j=1}^{N}\lambda_j \sum\nolimits_p \sum\nolimits_m \Theta_j^{-3} \tag{18-a}$$

$$D_2 = \frac{N_T}{\bar{\gamma}_A}\sum_{i=0}^{N_T-1}\left(\begin{array}{c} N_T - 1 \\ i \end{array}\right)\frac{(-1)^i C_2}{\mathrm{A}_i'}\sum_{j=1}^{N}\lambda_j \sum\nolimits_p \sum\nolimits_m \Theta_j^{-2} \tag{18-b}$$

$$D_3 = \frac{N_T}{\bar{\gamma}_A}\sum_{i=0}^{N_T-1}\left(\begin{array}{c} N_T - 1 \\ i \end{array}\right)\frac{(-1)^i C_3}{\mathrm{A}_i'}\sum_{j=1}^{N}\lambda_j \sum\nolimits_p \sum\nolimits_m \Theta_j^{-1}. \tag{18-c}$$

Substituting (18) into (17), we can obtain

$$SOP\left(C_{th}\right) = \frac{N_T}{\bar{\gamma}_A}\sum_{i=0}^{N_T-1}\left(\begin{array}{c} N_T - 1 \\ i \end{array}\right)\frac{(-1)^i}{\mathrm{A}_i'}\sum_{j=1}^{N}\lambda_j \sum\nolimits_p \cdot \sum\nolimits_m \left(2C_1\Theta_j^{-3} + C_2\Theta_j^{-2} + C_3\Theta_j^{-1}\right). \tag{19}$$

As suggested by [17], in the high SNR regime with $\bar{\gamma}_A \to \infty$, the asymptotic SOP can be expressed as

$$SOP_{\bar{\gamma}_A \to \infty} = \left(\Psi\bar{\gamma}_A\right)^{-\Phi} + o\left(\bar{\gamma}_A^{-\Phi}\right), \tag{20}$$

where $o(\cdot)$ denotes higher order terms, $\Phi = 1$ is the secrecy diversity gain, which determines the slope of the asymptotic outage probability curve, and Ψ is the secrecy array gain which can be expressed as $\Psi = \left[N_T \sum\limits_{i=0}^{N_T-1}\left(\begin{array}{c} N_T - 1 \\ i \end{array}\right)\frac{(-1)^i}{\mathrm{A}_i'}\sum\limits_{j=1}^{N}\lambda_j \sum_p \cdot \sum_m \left(\frac{\alpha}{\Theta_j^2} + \frac{\alpha - 1}{\Theta_j}\right)\right]^{-1}$.

IV. Numerical Results and Discussion

In this section, we compare simulation and analysis results for SOP. For simplicity, we assume that the link channels between BS and each ER experience independent and identically distributed Rayleigh fading. Unless otherwise explicitly specified, the parameters are set as P_t = 30 dBm, $\eta = 0$, $g_A = 1$, $N_T = N = 2$, $N_0 = 1$, $\sigma_i^2 = 1$ ($i \in \{1, \cdots, N\}$), $\rho_i = \rho = 0.5$ ($i \in \{1, \cdots, N\}$), and C_{th} = 0 dB. Simulation is performed by transmitting 1×10^6 bits and $\tau = g_A/h_{Ai}$ ($i \in \{1, \cdots, N\}$).

In Figs. 2-3, we present simulation and analytical results of SOP v.s. τ for various combinations of ρ and η, P_t/N_0 and combinations of N and N_T, respectively. Clearly, analytical results perfectly match with Monte-Carlo simulations, and SOP can be improved while τ increases, because a higher τ represents that the channel condition for BS-IR link outperforms the ones of BS-ER eavesdropping links.

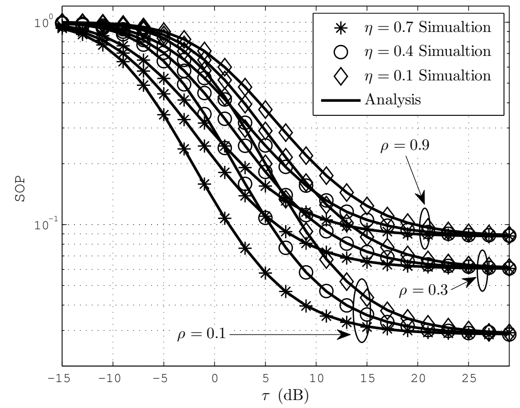

Fig. 2. SOP vs. τ for various combinations of ρ and η

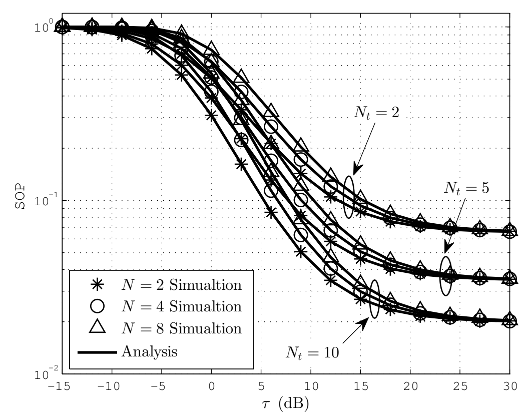

Fig. 3. SOP vs. τ for various combinations of N and N_T

As depicted in Fig. 2, the SOP with a lower ρ outperforms the one with a higher ρ. Because a higher ρ means a larger portion of the received signal power is split to the ID at each ER, then a higher received SNR at the ID of each ER, resulting in a higher eavesdropping capacity. Meanwhile, we can also see that the SOP with a higher η outperforms the one with a lower η due to the factor that a higher η represents a higher correlation between the channel gain of the link between the selected transmit antenna at BS and IR, g, and the one of the link between the selected transmit antenna at BS and IR at the selection instant, $\tilde{g}$.

As shown in Fig. 3, the SOP with a larger N_T outperforms the one with a smaller N_T due to the larger diversity gain benefited from the TAS scheme adopted at the BS. Further, the SOP with a small N outperforms the one with a larger N. It is because of a lower virtual diversity gain achieved among the ERs for the case of a smaller N. This can be easily explained by the definition of $\gamma_{\max}$ as shown below Eq. (1) in Section II.

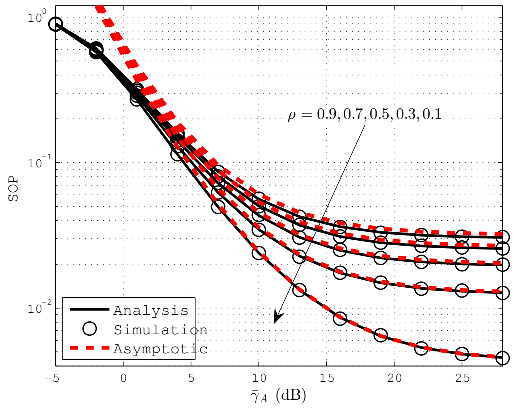

Fig. 4. SOP vs. $\bar{\gamma}_A$ for various ρ

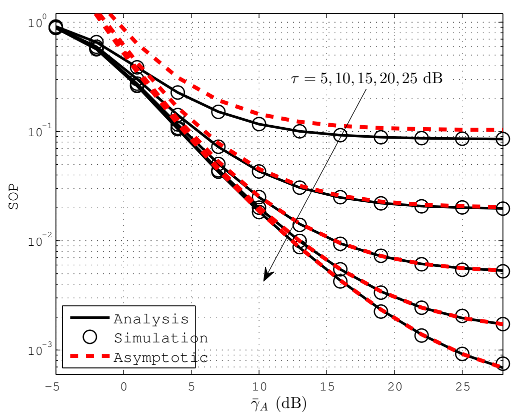

Fig. 5. SOP vs. $\bar{\gamma}_A$ for various τ

Figs. 4 and 5 present the SOP vs. $\bar{\gamma}_A$ for various ρ and τ, respectively, while $N_T = 3$ and $N = 4$. The asymptotic results for SOP are obtained from (19) in Section III. We can observe that our asymptotic results accurately predict the secrecy diversity order and secrecy diversity gain. As shown in Fig. 4, it can also be seen that the SOP with a lower ρ outperforms the one with a higher ρ. It is because that a lower ρ means less received signal power consumed on information decoding, leading to better SOP performance. Furthermore, it is clear that in Fig. 5 the SOP with a higher τ outperforms the one with a lower τ. Because BS-IR link gets better compared to BS-ER links as τ increases.

V. Conclusion

In this paper, we have investigated the secrecy performance of MISO SWIPT systems in the presence of imperfect CSI. The closed-form analytical expressions for the exact and the asymptotic secrecy outage probability has been derived while each eavesdropping link experiences independent not necessarily identically Rayleigh fading. The validity of the proposed analytical models has been testified through Monte-Carlo simulations.

VI. Acknowledgment

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