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Ergodic secrecy capacity of MRC/SC in single-input multiple-output wiretap systems with imperfect channel state information*

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Abstract: This paper investigates the secrecy performance of maximal ratio combining (MRC) and selection combining (SC) with imperfect channel state information (CSI) in the physical layer. In a single-input multiple-output (SIMO) wiretap channel, a source transmits confidential messages to the destination equipped with M antennas using the MRC/SC scheme to process the received multiple signals. An eavesdropper equipped with N antennas also adopts the MRC/SC scheme to promote successful eavesdropping. We derive the exact and asymptotic closed-form expressions for the ergodic secrecy capacity (ESC) in two cases: (1) MRC with weighting errors, and (2) SC with outdated CSI. Moreover, two important indicators, namely high signal-to-noise ratio (SNR) slope and high SNR power offset, which govern ESC at the high SNR region, are derived. Finally, simulations are conducted to validate the accuracy of our proposed analytical models. Results indicate that ESC rises with the increase of the number of antennas and the received SNR at the destination, and fades with the increase of those at the eavesdropper. Another finding is that the high SNR slope is constant, while the high SNR power offset is correlated with the number of antennas at both the destination and the eavesdropper.

Key words: Ergodic secrecy capacity (ESC); Maximal ratio combining (MRC); Weighting errors; Physical layer security; Selection combining (SC); Single-input multiple-output (SIMO)

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1 Introduction

Channel state information (CSI) cannot be obtained perfectly because of the complexity of electromagnetic wave spreading and transmitting delay. Thus, CSI has estimation errors at the receiver. Janarthanan and Bhaskar (2013) and Khuong and Sofotasios (2013) analyzed the capacity and bit-error-rate in single-input multiple-output (SIMO) and multi-hop cooperation systems with CSI estimation errors, respectively.

Due to the broadcast nature of wireless links, it is difficult to prevent eavesdroppers from overhearing wireless communications (Liu Y *et al.*, 2015; 2016). Thus, security issues play an important role in wireless networks. Physical layer security has been considered widely as an effective technology to prevent information from being intercepted (Shiu *et al.*, 2011; Yang *et al.*, 2015). In different fading scenarios, Sun *et al.* (2012), Zhang *et al.* (2014), Pan

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et al. (2015; 2016), Lei *et al.* (2015; 2016), and Liu H *et al.* (2016a) studied the secrecy performance over independent/correlated Rayleigh, log-normal, Rayleigh–log-normal, generalized-K, and generalized Gamma fading channels. In addition, maximal ratio combining (MRC) was used to improve the secrecy performance in He *et al.* (2011), Alves *et al.* (2012), Yang *et al.* (2013a; 2013b; 2013c), Wang *et al.* (2014a; 2014b), and Pan *et al.* (2015).

As an ideal diversity for linear systems, MRC is the best among the basic linear diversity combining schemes. However, due to the fact that the diversity weighting factors are proportional to the complex conjugate of the channel fading vector in time, when the pilot frequency range and channel bandwidth are similar, it is easy to cause a Gaussian channel estimation error, resulting in nonideal MRC diversity and degraded output-combined signal-to-noise ratio (SNR) (Gans, 1971). In addition, to isolate pilot from the signal in time, the signal and pilot are transmitted alternately. When this separation time is on the order of the reciprocal of the fading rate, the weighted factor obtained from the pilot will also have a Gaussian channel estimation error (Tomiuk *et al.*, 1999).

For the situation where the receiver and the eavesdropper show Gaussian errors at the same time, Shrestha and Kwark (2014) and Hu and Tao (2015) extended the work of Gans (1971) and Tomiuk *et al.* (1999), and studied the secrecy outage probability in SIMO and multiple-input multiple-output (MIMO) wiretap channels. Zhao and Pan (2016) investigated the secrecy outage performance of decode-and-forward and randomize-and-forward cooperative systems, considering the MRC scheme with weighting errors.

However, Shrestha and Kwark (2014), Hu and Tao (2015), and Zhao and Pan (2016) did not consider the ergodic secrecy capacity (ESC), which is one of the most important parameters in physical layer security (Wang *et al.*, 2014a; 2014b). Because of the rapid increase in the demand for wireless communication services, the capacity of fading channels is increasingly becoming a main concern in the design of wireless communication systems (Khatalin and Fonseka, 2006). In a Gaussian noise environment, the capacity is constant, because the carrier-to-noise ratio is constant. In fading channels, such as Rayleigh fading channels, the SNR of receivers varies with time. This offers an explanation why the capacity of fading channels has to be calculated in an average sense (Lee, 1990; Alouini and Goldsmith, 1999; Simon and Alouini, 2005). The derivation of a closed-form expression for the capacity over fading channels is of higher computational complexity compared to that of the outage probability, especially the ESC over wiretap channels, as logarithmic functions are presented in the integral equation (Rezki *et al.*, 2014).

Though MRC has better combining performance than selection combining (SC), SC has a lower complexity. Thus, SC is also a common combining technology in practical applications. In recent years, it has been adopted widely to improve the secrecy performance in the physical layer (Ferdinand *et al.*, 2013; Yang *et al.*, 2013a; 2013b; 2013c; Elkashlan *et al.*, 2015). However, due to the transmitting delay, the CSI obtained from the pilot at the receiver may be outdated, leading to an imperfect SC and the degradation of the combined SNR.

Motivated by the above observations, we analyze the secrecy performance of a SIMO wiretap system, where a source equipped with a single antenna transmits confidential messages to the destination equipped with M ($M \geq 1$) antennas using the MRC/SC scheme to process the received multiple signals. Meanwhile, an eavesdropper, which is equipped with N ($N \geq 1$) antennas, adopts the MRC/SC scheme to promote successful eavesdropping. We derive the exact and asymptotic closed-form expressions for the ESC over Rayleigh fading channels under two cases: (1) MRC with weighting errors and (2) SC with outdated CSI. Further, a high SNR slope and a high SNR power offset are derived, which govern ESC in the high SNR region.

According to the numerical results in Section 5, two key insights are obtained:

1. ESC rises with the increase of the number of antennas and the received SNR at the destination, and fades with the increase of those at the eavesdropper.

2. High SNR slope is constant, which means that high SNR slope is independent of the number of antennas and the received SNR at the destination and the eavesdropper. In contrast, high SNR power offset is correlated with the number of antennas at the destination and the eavesdropper.

2 System model

We consider a SIMO wiretap system, in which a source (S) equipped with a single antenna encodes the confidential messages into a transmitted codeword $\boldsymbol{x} = [x(1), x(2), \ldots, x(n)]$ using the capacity achieving codebook for the wiretap channel, which is subject to an average power constraint $\frac{1}{n}\sum_{i=1}^{n} E\left[|x(i)|^2\right] \le P_{\mathrm{S}}$. S transmits $\boldsymbol{x}$ to the destination (D), which is equipped with M ($M \ge 1$) antennas and adopts the MRC/SC scheme to improve its received SNR; an eavesdropper (E), which is equipped with N ($N \ge 1$) antennas, also adopts the MRC/SC scheme to promote successful eavesdropping. Here, perfect secrecy can be achieved by using a proper coding scheme when the received SNR of D is higher than that of E. $\boldsymbol{h}_M = [h_{\mathrm{D}_1}, h_{\mathrm{D}_2}, \ldots, h_{\mathrm{D}_M}]^{\mathrm{T}}$ and $\boldsymbol{h}_N = [h_{\mathrm{E}_1}, h_{\mathrm{E}_2}, \ldots, h_{\mathrm{E}_N}]^{\mathrm{T}}$ are the channel gain vectors of S–D and S–E links, respectively. In this study, we consider a practical passive eavesdropping scenario, which means that the CSI of the S–E link is unavailable at S; thus, S has no choice but to encode the confidential data into codewords of a constant rate (Elkashlan *et al.*, 2015). In contrast, both D and E are aware of their individual CSI accurately in the training period. Moreover, we assume that all considered channels in this study are subject to quasi-static Rayleigh fading, where the fading coefficients are constant over one fading block but vary independently from block to block, and the fading block lengths of S–D and S–E links are equal.

2.1 Maximal ratio combining scheme

If the receivers at D and E have full CSI of their own channels, the ideal combined signals of D and E are given by

$$y_{\mathrm{D}} = \sum_{u=1}^{M} \frac{h_{\mathrm{D}_u}^*}{N_{\mathrm{D}_u}} y_{\mathrm{D}_u}, \quad u = 1, 2, \ldots, M, \tag{1}$$

$$y_{\mathrm{E}} = \sum_{v=1}^{N} \frac{h_{\mathrm{E}_v}^*}{N_{\mathrm{E}_v}} y_{\mathrm{E}_v}, \quad v = 1, 2, \ldots, N, \tag{2}$$

respectively, where $h_{\mathrm{D}_u}^*$ and $h_{\mathrm{E}_v}^*$ represent the conjugate of h_{D_u} and h_{E_v}, respectively. Likewise, y_{D_u} and N_{D_u}, y_{E_v} and N_{E_v} represent the received signals and the mean square noise power of the uth and vth branches, respectively.

In the practical scenario, the combiner weights $h_{\mathrm{D}_u}^*/N_{\mathrm{D}_u}$ and $h_{\mathrm{E}_v}^*/N_{\mathrm{E}_v}$ cannot be obtained perfectly. A complex Gaussian error will result in the weighting factors, $\widehat{h}_{\mathrm{D}_u}^*$ and $\widehat{h}_{\mathrm{E}_v}^*$, which are the estimates of $h_{\mathrm{D}_u}^*$ and $h_{\mathrm{E}_v}^*$ derived from the pilot signal (Gans, 1971), respectively. The channel gain with weighting errors of D is given by Hu *et al.* (2015) as

$$\widehat{h}_{\mathrm{D}_u} = \sqrt{\rho_{\mathrm{D}}} h_{\mathrm{D}_u} + \sqrt{1-\rho_{\mathrm{D}}} g_{\mathrm{D}_u}, \tag{3}$$

where $\rho_{\mathrm{D}} \in [0, 1]$ is a power coefficient defined by Eq. (58) in Gans (1971), and g_{D_u} is a random variable which experiences the same distribution as h_{D_u}.

Let $\gamma_{\mathrm{D}} = \sum_{u=1}^{M} ((P_{\mathrm{S}}|\widehat{h}_{\mathrm{D}_u}|^2)/N_{\mathrm{D}_u})$ and $\gamma_{\mathrm{E}} = \sum_{v=1}^{N} ((P_{\mathrm{S}}|\widehat{h}_{\mathrm{E}_v}|^2)/N_{\mathrm{E}_v})$ be the instantaneous SNRs at D and E, respectively. The probability density functions (PDFs) of γ_{D} and γ_{E} are (Tomiuk *et al.*, 1999)

$$f_{\gamma_{\mathrm{D}}}(x) = \sum_{i=1}^{M} A(i) \frac{x^{i-1} \exp\left(-x/\overline{\gamma}_{\mathrm{D}}\right)}{\Gamma(i)\overline{\gamma}_{\mathrm{D}}^{i}}, \tag{4}$$

$$f_{\gamma_{\mathrm{E}}}(x) = \sum_{j=1}^{N} B(j) \frac{x^{j-1} \exp\left(-x/\overline{\gamma}_{\mathrm{E}}\right)}{\Gamma(j)\overline{\gamma}_{\mathrm{E}}^{j}}, \tag{5}$$

respectively, where $\overline{\gamma}_{\mathrm{D}}$ and $\overline{\gamma}_{\mathrm{E}}$ are the average per-antenna SNRs at D and E, respectively, $\Gamma(\cdot)$ is the Gamma function (Gradshteyn and Ryzhik, 2007), and $A(\cdot)$ and $B(\cdot)$ are

$$A(i) = \binom{M-1}{i-1} (1-\rho_{\mathrm{D}})^{M-i} \rho_{\mathrm{D}}^{i-1}, \tag{6}$$

$$B(j) = \binom{N-1}{j-1} (1-\rho_{\mathrm{E}})^{N-j} \rho_{\mathrm{E}}^{j-1}, \tag{7}$$

respectively, where $\rho_{\mathrm{E}} \in [0, 1]$ is the power correlation coefficient between the actual and estimated channel of S–E link..

Further, by applying the probability theory, we have

$$\int_0^{\infty} f_{\gamma_{\mathrm{D}}}(x)\,\mathrm{d}x = \sum_{i=1}^{M} A(i) \frac{1}{\gamma(i)\overline{\gamma}_{\mathrm{D}}^{i}} \cdot \int_0^{\infty} x^{i-1} \exp\left(-\frac{x}{\overline{\gamma}_{\mathrm{D}}}\right) \mathrm{d}x = 1. \tag{8}$$

Using Eq. (3.326.2) in Gradshteyn and Ryzhik (2007), we can derive $\sum_{i=1}^{M} A(i) = 1$. The cumulative PDFs of γ_{D} and γ_{E} can be given by (Shrestha and

Kwark, 2014)

$$F_{\gamma_{\mathrm{D}}}(x)=\sum_{i=1}^{M}A(i)\left(1-\frac{\Gamma\left(i,x/\overline{\gamma}_{\mathrm{D}}\right)}{\Gamma(i)}\right), \quad (9)$$

$$F_{\gamma_{\mathrm{E}}}(x)=\sum_{j=1}^{N}B(j)\left(1-\frac{\Gamma\left(j,x/\overline{\gamma}_{\mathrm{E}}\right)}{\Gamma(j)}\right), \quad (10)$$

respectively, where $\Gamma(\cdot,\cdot)$ is the upper incomplete Gamma function (Gradshteyn and Ryzhik, 2007).

2.2 Selection combining scheme

In the SC scenario, before receiving confidential messages from S, D performs antenna selection using the CSI obtained from the pilot, and therefore the channel gain of the selected antenna can be written as $h_{\mathrm{D_s}}=\max\limits_{u\in\{1,2,\ldots,M\}}|h_{\mathrm{D}_u}|$. Similarly, we have $h_{\mathrm{E_s}}=\max\limits_{v\in\{1,2,\ldots,N\}}|h_{\mathrm{E}_v}|$.

After antenna selection, D receives the messages from S via the selected antenna. However, because of transmitting delay, the CSI of the received signal at D is normally different from the one during antenna selection. We assume that $\widetilde{h}_{\mathrm{D_s}}$ denotes the τ_{d} time-delayed channel coefficient version of $h_{\mathrm{D_s}}$. The SNR at D can be written as $\gamma_{\mathrm{D}}=(P_{\mathrm{S}}|\widetilde{h}_{\mathrm{B_s}}|^2)/N_0$, where N_0 denotes the AWGN's power. Similarly, we have $\gamma_{\mathrm{E}}=(P_{\mathrm{S}}|\widetilde{h}_{\mathrm{E_s}}|^2)/N_0$, where $\widetilde{h}_{\mathrm{E_s}}$ denotes the τ_{e} time-delayed channel coefficient version of $h_{\mathrm{E_s}}$.

3 Ergodic secrecy capacity of maximal ratio combining scheme

In this section, we consider that both D and E adopt MRC with weighting errors to improve their received SNR. The exact and asymptotic closed-form expressions for the ESC of MRC with weighting errors are derived.

The instantaneous secrecy capacity is given by (Shrestha and Kwark, 2014)

$$C_{\mathrm{S}}=\begin{cases}\ln(1+\gamma_{\mathrm{D}})-\ln(1+\gamma_{\mathrm{E}}),\ \gamma_{\mathrm{D}}>\gamma_{\mathrm{E}},\\ 0,\ \gamma_{\mathrm{D}}\le\gamma_{\mathrm{E}}.\end{cases} \quad (11)$$

Thus, we can write ESC as

$$\overline{C}_{\mathrm{S}}(\gamma_{\mathrm{D}},\gamma_{\mathrm{E}})=\int_0^\infty\int_0^\infty C_{\mathrm{S}}f_{\gamma_{\mathrm{D}}}(\gamma_{\mathrm{D}})f_{\gamma_{\mathrm{E}}}(\gamma_{\mathrm{E}})\,\mathrm{d}\gamma_{\mathrm{D}}\mathrm{d}\gamma_{\mathrm{E}}. \quad (12)$$

After some mathematical manipulation, we can obtain

$$\begin{aligned}\overline{C}_{\mathrm{S}}(\gamma_{\mathrm{D}},\gamma_{\mathrm{E}})&=\int_0^\infty\int_0^{\gamma_{\mathrm{D}}}C_{\mathrm{S}}f_{\gamma_{\mathrm{D}}}(\gamma_{\mathrm{D}})f_{\gamma_{\mathrm{E}}}(\gamma_{\mathrm{E}})\,\mathrm{d}\gamma_{\mathrm{E}}\,\mathrm{d}\gamma_{\mathrm{D}}\\&\quad+\int_0^\infty\int_{\gamma_{\mathrm{D}}}^\infty C_{\mathrm{S}}f_{\gamma_{\mathrm{D}}}(\gamma_{\mathrm{D}})f_{\gamma_{\mathrm{E}}}(\gamma_{\mathrm{E}})\,\mathrm{d}\gamma_{\mathrm{E}}\,\mathrm{d}\gamma_{\mathrm{D}}\\&=\int_0^\infty\ln(1+\gamma_{\mathrm{D}})f_{\gamma_{\mathrm{D}}}(\gamma_{\mathrm{D}})\cdot\int_0^{\gamma_{\mathrm{D}}}f_{\gamma_{\mathrm{E}}}(\gamma_{\mathrm{E}})\,\mathrm{d}\gamma_{\mathrm{E}}\,\mathrm{d}\gamma_{\mathrm{D}}\\&\quad-\int_0^\infty\ln(1+\gamma_{\mathrm{E}})f_{\gamma_{\mathrm{E}}}(\gamma_{\mathrm{E}})\cdot\int_{\gamma_{\mathrm{E}}}^\infty f_{\gamma_{\mathrm{D}}}(\gamma_{\mathrm{D}})\,\mathrm{d}\gamma_{\mathrm{D}}\,\mathrm{d}\gamma_{\mathrm{E}},\end{aligned} \quad (13)$$

which provides a general form to obtain the closed-form expression for the ESC over fading channels. In the following, the ESC analysis of SC with outdated CSI also adopts this integral equation.

Let

$$\overline{C}_{\mathrm{D}}=\int_0^\infty\ln(1+\gamma_{\mathrm{D}})f_{\gamma_{\mathrm{D}}}(\gamma_{\mathrm{D}})\int_0^{\gamma_{\mathrm{D}}}f_{\gamma_{\mathrm{E}}}(\gamma_{\mathrm{E}})\,\mathrm{d}\gamma_{\mathrm{E}}\,\mathrm{d}\gamma_{\mathrm{D}},$$

and

$$\overline{C}_{\mathrm{E}}=\int_0^\infty\ln(1+\gamma_{\mathrm{E}})f_{\gamma_{\mathrm{E}}}(\gamma_{\mathrm{E}})\int_{\gamma_{\mathrm{E}}}^\infty f_{\gamma_{\mathrm{D}}}(\gamma_{\mathrm{D}})\,\mathrm{d}\gamma_{\mathrm{D}}\,\mathrm{d}\gamma_{\mathrm{E}}.$$

We establish Theorem 1 as follows:

Theorem 1 The closed-form expression for the ESC of MRC with weighting errors is derived as

$$\overline{C}_{\mathrm{S\_MRC}}=\overline{C}_{\mathrm{D\_MRC}}-\overline{C}_{\mathrm{E\_MRC}}, \quad (14)$$

where $\overline{C}_{\mathrm{D\_MRC}}$ and $\overline{C}_{\mathrm{E\_MRC}}$ will be derived in Eqs. (23) and (27), respectively.

Proof See Sections 3.1 and 3.2.

3.1 Derivation of $\overline{C}_{\mathrm{D\_MRC}}$

We can rewrite $\overline{C}_{\mathrm{D\_MRC}}$ as

$$\overline{C}_{\mathrm{D\_MRC}}=\int_0^\infty\ln(1+\gamma_{\mathrm{D}})f_{\gamma_{\mathrm{D}}}(\gamma_{\mathrm{D}})F_{\gamma_{\mathrm{E}}}(\gamma_{\mathrm{D}})\,\mathrm{d}\gamma_{\mathrm{D}}. \quad (15)$$

Substituting the PDF of γ_{D} and the cumulative density function (CDF) of γ_{E} into Eq. (15), we have Eq. (16). I_1 can be rewritten as Eq. (17). Eqs. (16) and (17) are shown on the next page.

We consider the integral equation given in Appendix B in Alouini and Goldsmith (1999) as

$$\begin{aligned}&\int_0^\infty\ln(1+x)x^{n-1}\exp(-ux)\,\mathrm{d}x\\&\quad=(n-1)!\exp(u)\sum_{l=1}^{n}\frac{\Gamma(-n+l,u)}{u^l},\end{aligned} \quad (18)$$

$$\overline{C}_{\mathrm{D\_MRC}}=\sum_{i=1}^{M}\sum_{j=1}^{N}A(i)B(j)\frac{1}{\Gamma(i)\,\overline{\gamma}_{\mathrm{D}}^{i}}\underbrace{\int_{0}^{\infty}\ln(1+\gamma_{\mathrm{D}})\,\gamma_{\mathrm{D}}^{i-1}\exp\left(-\frac{\gamma_{\mathrm{D}}}{\overline{\gamma}_{\mathrm{D}}}\right)\left(1-\frac{\Gamma\left(j,\gamma_{\mathrm{D}}/\overline{\gamma}_{\mathrm{E}}\right)}{\Gamma(j)}\right)\mathrm{d}\gamma_{\mathrm{D}}}_{I_1}. \tag{16}$$

$$I_1\left(\overline{\gamma}_{\mathrm{D}},\overline{\gamma}_{\mathrm{E}},i,j\right)=\underbrace{\int_{0}^{\infty}\ln(1+\gamma_{\mathrm{D}})\,\gamma_{\mathrm{D}}^{i-1}\exp\left(-\frac{\gamma_{\mathrm{D}}}{\overline{\gamma}_{\mathrm{D}}}\right)\mathrm{d}\gamma_{\mathrm{D}}}_{Q_1}-\underbrace{\frac{1}{\Gamma(j)}\int_{0}^{\infty}\ln(1+\gamma_{\mathrm{D}})\,\gamma_{\mathrm{D}}^{i-1}\exp\left(-\frac{\gamma_{\mathrm{D}}}{\overline{\gamma}_{\mathrm{D}}}\right)\Gamma\left(j,\gamma_{\mathrm{D}}/\overline{\gamma}_{\mathrm{E}}\right)\mathrm{d}\gamma_{\mathrm{D}}}_{Q_2}. \tag{17}$$

where $\Gamma(\cdot,\cdot)$ is the complementary incomplete Gamma function, which is given by

$$\begin{aligned}\Gamma(a,z)&=\exp(-z)\cdot U(1-a,1-a,z)\\&=\exp(-z)\cdot z^{a-1}\cdot{}_2F_0(1-a,1;;-z^{-1}),\end{aligned} \tag{19}$$

where $U(\cdot,\cdot,\cdot)$ is the second kind of confluent hypergeometric function and ${}_2F_0(\cdot,\cdot;;\cdot)$ is the hypergeometric function (Gradshteyn *et al.*, 2007). Note that as the complementary incomplete Gamma function cannot be directly calculated in Matlab, we transform $\Gamma(\cdot,\cdot)$ in Eq. (18) into the form of hypergeometric function.

Using Eq. (18), we can derive Q_1 as

$$\begin{aligned}&Q_1\left(\overline{\gamma}_{\mathrm{D}},i\right)\\&\quad=(i-1)!\exp\left(\frac{1}{\overline{\gamma}_{\mathrm{D}}}\right)\sum_{p=1}^{i}\frac{\Gamma\left(-i+p,1/\overline{\gamma}_{\mathrm{D}}\right)}{\left(1/\overline{\gamma}_{\mathrm{D}}\right)^{p}}.\end{aligned} \tag{20}$$

Expanding $\Gamma(\cdot,\cdot)$ into the form of the series in Q_2, we have Eq. (21), as shown on the next page.

Substituting Eqs. (20) and (21) into Eq. (17), it follows

$$I_1(\overline{\gamma}_{\mathrm{D}},\overline{\gamma}_{\mathrm{E}},i,j)=Q_1(\overline{\gamma}_{\mathrm{D}},i)-Q_2(\overline{\gamma}_{\mathrm{D}},\overline{\gamma}_{\mathrm{E}},i,j). \tag{22}$$

Finally, substituting Eq. (22) into Eq. (16), we can obtain

$$\overline{C}_{\mathrm{D\_MRC}}=\sum_{i=1}^{M}\sum_{j=1}^{N}A(i)B(j)\frac{1}{\Gamma(i)\,\overline{\gamma}_{\mathrm{D}}^{i}}I_1\left(\overline{\gamma}_{\mathrm{D}},\overline{\gamma}_{\mathrm{E}},i,j\right). \tag{23}$$

3.2 Derivation of $\overline{C}_{\mathrm{E\_MRC}}$

We can rewrite $\overline{C}_{\mathrm{E\_MRC}}$ as Eq. (24), as shown on the next page.

Substituting the PDF of γ_{E} into I_2 and using Eq. (18), we have

$$\begin{aligned}&I_2\left(N,\overline{\gamma}_{\mathrm{E}},\rho_{\mathrm{E}}\right)\\&\quad=\sum_{j=1}^{N}B(j)\frac{1}{\Gamma(j)\overline{\gamma}_{\mathrm{E}}^{j}}\int_{0}^{\infty}\ln(1+\gamma_{\mathrm{E}})\,\gamma_{\mathrm{E}}^{j-1}\\&\qquad\cdot\exp\left(-\frac{\gamma_{\mathrm{E}}}{\overline{\gamma}_{\mathrm{E}}}\right)\mathrm{d}\gamma_{\mathrm{E}}\\&\quad=\sum_{j=1}^{N}B(j)\exp\left(1/\overline{\gamma}_{\mathrm{E}}\right)\sum_{q=1}^{j}\overline{\gamma}_{\mathrm{E}}^{q-j}\Gamma\left(-j+q,1/\overline{\gamma}_{\mathrm{E}}\right).\end{aligned} \tag{25}$$

Considering that the PDFs of γ_{D} and γ_{E} are similar and the equations of $\overline{C}_{\mathrm{D\_MRC}}$ and I_3 have the same structure, we can rewrite I_3 as

$$\begin{aligned}&I_3\left(M,N,\overline{\gamma}_{\mathrm{D}},\overline{\gamma}_{\mathrm{E}},\rho_{\mathrm{D}},\rho_{\mathrm{E}}\right)\\&\quad=\sum_{i=1}^{M}\sum_{j=1}^{N}A(i)B(j)\frac{1}{\Gamma(j)\overline{\gamma}_{\mathrm{E}}^{j}}I_1\left(\overline{\gamma}_{\mathrm{E}},\overline{\gamma}_{\mathrm{D}},j,i\right).\end{aligned} \tag{26}$$

Here, it is important to note the parameters' order in $I_1(\cdot,\cdot,\cdot,\cdot)$ and $I_3(\cdot,\cdot,\cdot,\cdot,\cdot,\cdot)$.

Substituting Eqs. (25) and (26) into Eq. (24), we can derive the closed-form expression for $\overline{C}_{\mathrm{E\_MRC}}$ as

$$\begin{aligned}\overline{C}_{\mathrm{E\_MRC}}&=I_2\left(N,\overline{\gamma}_{\mathrm{E}},\rho_{\mathrm{E}}\right)\\&\quad-I_3\left(M,N,\overline{\gamma}_{\mathrm{D}},\overline{\gamma}_{\mathrm{E}},\rho_{\mathrm{D}},\rho_{\mathrm{E}}\right).\end{aligned} \tag{27}$$

Finally, ESC can be obtained by substituting $\overline{C}_{\mathrm{D\_MRC}}$ and $\overline{C}_{\mathrm{E\_MRC}}$ into Eq. (13).

3.3 Asymptotic ergodic secrecy capacity of maximal ratio combining

In this section, we analyze the asymptotic ESC when $\overline{\gamma}_{\mathrm{D}}\to\infty$, while $\overline{\gamma}_{\mathrm{E}}$ is finite.

$$Q_2\left(\overline{\gamma}_{\mathrm{D}},\overline{\gamma}_{\mathrm{E}},i,j\right)=\sum_{n=0}^{j-1}\frac{1}{\overline{\gamma}_{\mathrm{E}}^{n}n!}\int_0^{\infty}\ln\left(1+\gamma_{\mathrm{D}}\right)\gamma_{\mathrm{D}}^{i+n-1}\cdot\exp\left[-\left(\frac{1}{\overline{\gamma}_{\mathrm{E}}}+\frac{1}{\overline{\gamma}_{\mathrm{D}}}\right)\gamma_{\mathrm{D}}\right]\mathrm{d}\gamma_{\mathrm{D}}$$
$$=\sum_{n=0}^{j-1}\frac{1}{\overline{\gamma}_{\mathrm{E}}^{n}n!}\left(i+n-1\right)!\exp\left(\frac{1}{\overline{\gamma}_{\mathrm{E}}}+\frac{1}{\overline{\gamma}_{\mathrm{D}}}\right)\cdot\sum_{q=1}^{i+n}\frac{\Gamma\left(-i-n+q,1/\overline{\gamma}_{\mathrm{E}}+1/\overline{\gamma}_{\mathrm{D}}\right)}{\left(1/\overline{\gamma}_{\mathrm{E}}+1/\overline{\gamma}_{\mathrm{D}}\right)^{q}}. \tag{21}$$

$$\overline{C}_{\mathrm{E\_MRC}}=\int_0^{\infty}\ln\left(1+\gamma_{\mathrm{E}}\right)f_{\gamma_{\mathrm{E}}}\left(\gamma_{\mathrm{E}}\right)\cdot\left[1-F_{\gamma_{\mathrm{D}}}\left(\gamma_{\mathrm{E}}\right)\right]\mathrm{d}\gamma_{\mathrm{E}}$$
$$=\underbrace{\int_0^{\infty}\ln\left(1+\gamma_{\mathrm{E}}\right)f_{\gamma_{\mathrm{E}}}\left(\gamma_{\mathrm{E}}\right)\mathrm{d}\gamma_{\mathrm{E}}}_{I_2}-\underbrace{\int_0^{\infty}\ln\left(1+\gamma_{\mathrm{E}}\right)f_{\gamma_{\mathrm{E}}}\left(\gamma_{\mathrm{E}}\right)F_{\gamma_{\mathrm{D}}}\left(\gamma_{\mathrm{E}}\right)\mathrm{d}\gamma_{\mathrm{E}}}_{I_3}. \tag{24}$$

Using $\Gamma(n+1,x)=n!\exp(-x)\sum_{r=0}^{n}\frac{x^r}{r!}$ $(n=0,1,\dots)$, and considering Eq. (8.352.4) in Gradshteyn and Ryzhik (2007), we can rewrite $F_{\gamma_{\mathrm{D}}}(x)$ as

$$F_{\gamma_{\mathrm{D}}}(x)=\sum_{i=1}^{M}A\left(i\right)\left[1-\exp\left(-\frac{x}{\overline{\gamma}_{\mathrm{D}}}\right)\sum_{r=0}^{i-1}\frac{x^r}{r!\overline{\gamma}_{\mathrm{D}}^{r}}\right]. \tag{28}$$

For $\sum_{i=1}^{M}A(i)=1$, $F_{\gamma_{\mathrm{D}}}(x)$ can be rewritten as

$$F_{\gamma_{\mathrm{D}}}(x)=1-\sum_{i=1}^{M}A(i)\exp\left(-\frac{x}{\overline{\gamma}_{\mathrm{D}}}\right)\sum_{r=0}^{i-1}\frac{x^r}{r!\overline{\gamma}_{\mathrm{D}}^{r}}. \tag{29}$$

Similarly, we can rewrite $F_{\gamma_{\mathrm{E}}}(x)$ as

$$F_{\gamma_{\mathrm{E}}}(x)=1-\sum_{j=1}^{N}B(j)\exp\left(-\frac{x}{\overline{\gamma}_{\mathrm{E}}}\right)\sum_{m=0}^{j-1}\frac{x^m}{m!\overline{\gamma}_{\mathrm{E}}^{m}}$$
$$=1-\chi_{\gamma_{\mathrm{E}}}(x), \tag{30}$$

where $\chi_{\gamma_{\mathrm{E}}}(x)=\sum_{j=1}^{N}B(j)\exp\left(-\frac{x}{\overline{\gamma}_{\mathrm{E}}}\right)\sum_{m=0}^{j-1}\frac{x^m}{m!\overline{\gamma}_{\mathrm{E}}^{m}}$.

As the CDF of MRC with Gaussian errors can be regarded as the weighted sum of multiple CDFs of MRC with perfect combinations (Shrestha and Kwark, 2014), to simplify the derivation of the closed form of asymptotic ESC when $\overline{\gamma}_{\mathrm{D}}\to\infty$, we can write the asymptotic ESC by using Eq. (22) in Wang *et al.* (2014a), as

$$\overline{C}_{\mathrm{S}}^{\infty}=\underbrace{\int_0^{\infty}\ln\gamma_{\mathrm{D}}f_{\gamma_{\mathrm{D}}}(\gamma_{\mathrm{D}})\,\mathrm{d}\gamma_{\mathrm{D}}}_{I_4}-\underbrace{\int_0^{\infty}\frac{\chi_{\gamma_{\mathrm{E}}}(\gamma_{\mathrm{E}})}{1+\gamma_{\mathrm{E}}}\,\mathrm{d}\gamma_{\mathrm{E}}}_{I_5}. \tag{31}$$

Considering the closed-form expressions for I_4 and I_5 in Eqs. (A1)–(A4) in the Appendix, the asymptotic ESC can be analyzed. To gain more insight, we evaluate the high SNR slope and the high SNR power offset, which determine the ESC in the high SNR regime.

We rewrite the asymptotic ESC in a general form as (given by Eq. (24) in Wang *et al.* (2014a))

$$\overline{C}_{\mathrm{S}}^{\infty}=S_{\infty}\left(\ln\overline{\gamma}_{\mathrm{D}}-\Omega_{\infty}\right), \tag{32}$$

where S_∞ is the high SNR slope in nat/(s·Hz) (3 dB) and Ω_∞ is the high SNR power offset in 3 dB unit.

We can rewrite the high SNR slope as $S_\infty=\lim_{\overline{\gamma}_{\mathrm{D}}\to\infty}\overline{C}_{\mathrm{S}}^{\infty}/\ln\overline{\gamma}_{\mathrm{D}}$. Obviously, $S_\infty=1$. We can conclude that the number of antennas at D and E has no impact on the high SNR slope.

We can express the high SNR power offset Ω_∞ as

$$\Omega_{\infty}=\lim_{\overline{\gamma}_{\mathrm{D}}\to\infty}\left(\ln\overline{\gamma}_{\mathrm{D}}-\frac{\overline{C}_{\mathrm{S}}^{\infty}}{S_{\infty}}\right)=\Omega_{\infty}^{M}+\Omega_{\infty}^{N}, \tag{33}$$

where $\Omega_{\infty}^{M}=-\sum_{i=1}^{M}A(i)\psi(i)$ and $\Omega_{\infty}^{N}=I_5$. We find that the high SNR power offset is independent of $\overline{\gamma}_{\mathrm{D}}$. We highlight that Ω_{∞}^{M} assesses the benefits of M on ESC, and Ω_{∞}^{N} quantifies the loss of ESC due to eavesdropping.

4 Ergodic secrecy capacity of selection combining scheme

In this section, we investigate the ESC of SC when both D and E adopt SC with outdated CSI to

improve their received SNR. The exact and asymptotic closed-form expressions for SC are derived.

4.1 Probability and cumulative density functions of selection combining with outdated imperfect channel state information

Considering Eq. (3), we have the PDF of γ_{D} using SC with outdated CSI as (given by Eq. (10) in Ferdinand *et al.* (2013))

$$f_{\gamma_{\mathrm{D}}}(x)=\int_0^{\infty} f_{\gamma_{\mathrm{D}}|\gamma_{\mathrm{d}}}(x|z)f_{\gamma_{\mathrm{d}}}(z)\,\mathrm{d}z. \tag{34}$$

Note that the correlation expression of the actual and the outdated channels gain under the SC scheme has the same form as that under the MRC scheme with weighting errors (Ferdinand *et al.*, 2013). In addition, ρ_{D} and ρ_{E} are power coefficients defined by Eq. (58) in Gans (1971). In Eq. (34), $f_{\gamma_{\mathrm{d}}}(\cdot)$ is the PDF of γ_{D} in the scenario with perfect CSI, given by

$$\begin{aligned} f_{\gamma_{\mathrm{d}}}(z)&=M\cdot F_{\gamma_{\mathrm{d},k}}^{M-1}(z)\cdot f_{\gamma_{\mathrm{d},k}}(z)\\ &=\frac{M}{\overline{\gamma}_{\mathrm{D}}}\sum_{m_1=0}^{M-1}\binom{M-1}{m_1}(-1)^{m_1}\\ &\quad\cdot\exp\left(-\frac{m_1+1}{\overline{\gamma}_{\mathrm{D}}}z\right), \end{aligned} \tag{35}$$

where $f_{\gamma_{\mathrm{d},k}}(\cdot)$ and $F_{\gamma_{\mathrm{d},k}}(\cdot)$ are the PDF and CDF of the receiving SNR at the kth antenna which experiences an exponential fading, respectively.

Using Eq. (13) in Ferdinand *et al.* (2013), we can derive the PDF of γ_{D} as

$$\begin{aligned} f_{\gamma_{\mathrm{D}}}(x)&=\underbrace{M\sum_{m_1=0}^{M-1}(-1)^{m_1}\binom{M-1}{m_1}\frac{1}{1-\rho_{\mathrm{D}}}\frac{1}{\alpha_{\mathrm{D}}\overline{\gamma}_{\mathrm{D}}}}_{\Sigma_{\Omega_{\mathrm{D}}}}\\ &\quad\cdot\exp\left(-\frac{\varsigma_{\mathrm{D}}x}{\overline{\gamma}_{\mathrm{D}}}\right)=\sum_{\Omega_{\mathrm{D}}}\exp\left(-\frac{\varsigma_{\mathrm{D}}x}{\overline{\gamma}_{\mathrm{D}}}\right), \end{aligned} \tag{36}$$

where $\alpha_{\mathrm{D}}=\dfrac{\rho_{\mathrm{D}}}{1-\rho_{\mathrm{D}}}+m_1+1$ and $\varsigma_{\mathrm{D}}=\dfrac{1}{1-\rho_{\mathrm{D}}}-\dfrac{\rho_{\mathrm{D}}}{\alpha_{\mathrm{D}}(1-\rho_{\mathrm{D}})^2}$.

The CDF of γ_{D} can be given by

$$\begin{aligned} F_{\gamma_{\mathrm{D}}}(x)&=\int_0^x\sum_{\Omega_{\mathrm{D}}}\exp\left(-\frac{\varsigma_{\mathrm{D}}}{\overline{\gamma}_{\mathrm{D}}}u\right)\mathrm{d}u\\ &=\sum_{\Omega_{\mathrm{D}}}\frac{\overline{\gamma}_{\mathrm{D}}}{\varsigma_{\mathrm{D}}}\left[1-\exp\left(-\frac{\varsigma_{\mathrm{D}}x}{\overline{\gamma}_{\mathrm{D}}}\right)\right]. \end{aligned} \tag{37}$$

Similarly, we can derive the PDF and CDF of γ_{E} as

$$\begin{aligned} f_{\gamma_{\mathrm{E}}}(x)&=\underbrace{N\sum_{n_1=0}^{N-1}(-1)^{n_1}\binom{N-1}{n_1}\frac{1}{1-\rho_{\mathrm{E}}}\frac{1}{\alpha_{\mathrm{E}}\overline{\gamma}_{\mathrm{E}}}}_{\Sigma_{\Omega_{\mathrm{E}}}}\\ &\quad\cdot\exp\left(-\frac{\varsigma_{\mathrm{E}}x}{\overline{\gamma}_{\mathrm{E}}}\right)=\sum_{\Omega_{\mathrm{E}}}\exp\left(-\frac{\varsigma_{\mathrm{E}}x}{\overline{\gamma}_{\mathrm{E}}}\right), \end{aligned} \tag{38}$$

$$F_{\gamma_{\mathrm{E}}}(x)=\sum_{\Omega_{\mathrm{E}}}\frac{\overline{\gamma}_{\mathrm{E}}}{\varsigma_{\mathrm{E}}}\left[1-\exp\left(-\frac{\varsigma_{\mathrm{E}}x}{\overline{\gamma}_{\mathrm{E}}}\right)\right], \tag{39}$$

where $\alpha_{\mathrm{E}}=\dfrac{\rho_{\mathrm{E}}}{1-\rho_{\mathrm{E}}}+n_1+1$ and $\varsigma_{\mathrm{E}}=\dfrac{1}{1-\rho_{\mathrm{E}}}-\dfrac{\rho_{\mathrm{E}}}{\alpha_{\mathrm{E}}(1-\rho_{\mathrm{E}})^2}$.

4.2 Ergodic secrecy capacity of selection combining

Theorem 2 The closed-form expression for the ESC of SC with outdated CSI is derived as

$$\overline{C}_{\mathrm{S\_SC}}=\overline{C}_{\mathrm{D\_SC}}-\overline{C}_{\mathrm{E\_SC}}, \tag{40}$$

where $\overline{C}_{\mathrm{D\_SC}}$ and $\overline{C}_{\mathrm{E\_SC}}$ will be derived as Eqs. (44) and (48), respectively.

Proof See Sections 4.2.1 and 4.2.2.

4.2.1 Derivation of $\overline{C}_{\mathrm{D\_SC}}$

We have $\overline{C}_{\mathrm{D\_SC}}$ as

$$\begin{aligned} &\overline{C}_{\mathrm{D\_SC}}\left(M,N,\overline{\gamma}_{\mathrm{D}},\overline{\gamma}_{\mathrm{E}},\rho_{\mathrm{D}},\rho_{\mathrm{E}}\right)\\ &\quad=\int_0^{\infty}\ln\left(1+\gamma_{\mathrm{D}}\right)f_{\gamma_{\mathrm{D}}}\left(\gamma_{\mathrm{D}}\right)F_{\gamma_{\mathrm{E}}}\left(\gamma_{\mathrm{D}}\right)\mathrm{d}\gamma_{\mathrm{D}}. \end{aligned} \tag{41}$$

Substituting the PDF of γ_{D} and the CDF of γ_{E} into the above equation, we can rewrite $\overline{C}_{\mathrm{D\_SC}}$ as Eq. (42), shown on the next page.

To simplify the analysis, we consider the following integral equation:

$$\begin{aligned} \Phi_1(a)&=\int_0^{\infty}\ln\left(1+\gamma_{\mathrm{D}}\right)\exp\left(-a\gamma_{\mathrm{D}}\right)\mathrm{d}\gamma_{\mathrm{D}}\\ &=\exp(a)\,\frac{\Gamma(0,a)}{a}, \end{aligned} \tag{43}$$

where $a>0$.

$$\begin{aligned}&\overline{C}_{\mathrm{D\_SC}}\left(M,N,\overline{\gamma}_{\mathrm{D}},\overline{\gamma}_{\mathrm{E}},\rho_{\mathrm{D}},\rho_{\mathrm{E}}\right)\\&=\sum_{\Omega_{\mathrm{D}}}\sum_{\Omega_{\mathrm{E}}}\frac{\overline{\gamma}_{\mathrm{E}}}{\varsigma_{\mathrm{E}}}\int_0^{\infty}\ln\left(1+\gamma_{\mathrm{D}}\right)\exp\left(-\frac{\varsigma_{\mathrm{D}}\gamma_{\mathrm{D}}}{\overline{\gamma}_{\mathrm{D}}}\right)\cdot\left[1-\exp\left(-\frac{\varsigma_{\mathrm{E}}\gamma_{\mathrm{D}}}{\overline{\gamma}_{\mathrm{E}}}\right)\right]\mathrm{d}\gamma_{\mathrm{D}}\\&=\sum_{\Omega_{\mathrm{D}}}\sum_{\Omega_{\mathrm{E}}}\frac{\overline{\gamma}_{\mathrm{E}}}{\varsigma_{\mathrm{E}}}\left\{\int_0^{\infty}\ln\left(1+\gamma_{\mathrm{D}}\right)\exp\left(-\frac{\varsigma_{\mathrm{D}}\gamma_{\mathrm{D}}}{\overline{\gamma}_{\mathrm{D}}}\right)\mathrm{d}\gamma_{\mathrm{D}}-\int_0^{\infty}\ln\left(1+\gamma_{\mathrm{D}}\right)\exp\left[-\left(\frac{\varsigma_{\mathrm{D}}}{\overline{\gamma}_{\mathrm{D}}}+\frac{\varsigma_{\mathrm{E}}}{\overline{\gamma}_{\mathrm{E}}}\right)\gamma_{\mathrm{D}}\right]\mathrm{d}\gamma_{\mathrm{D}}\right\}.\end{aligned}\tag{42}$$

Using the above integral equation, we can derive the closed-form expression for $\overline{C}_{\mathrm{D\_SC}}$ as

$$\begin{aligned}&\overline{C}_{\mathrm{D\_SC}}\left(M,N,\overline{\gamma}_{\mathrm{D}},\overline{\gamma}_{\mathrm{E}},\rho_{\mathrm{D}},\rho_{\mathrm{E}}\right)\\&=\sum_{\Omega_{\mathrm{D}}}\sum_{\Omega_{\mathrm{E}}}\frac{\overline{\gamma}_{\mathrm{E}}}{\varsigma_{\mathrm{E}}}\left[\Phi_1\left(\frac{\varsigma_{\mathrm{D}}}{\overline{\gamma}_{\mathrm{D}}}\right)-\Phi_1\left(\frac{\varsigma_{\mathrm{D}}}{\overline{\gamma}_{\mathrm{D}}}+\frac{\varsigma_{\mathrm{E}}}{\overline{\gamma}_{\mathrm{E}}}\right)\right].\end{aligned}\tag{44}$$

4.2.2 Derivation of $\overline{C}_{\mathrm{E\_SC}}$

We can write $\overline{C}_{\mathrm{E\_SC}}$ as

$$\begin{aligned}\overline{C}_{\mathrm{E\_SC}}&=\int_0^{\infty}\ln\left(1+\gamma_{\mathrm{E}}\right)f_{\gamma_{\mathrm{E}}}\left(\gamma_{\mathrm{E}}\right)\left[1-F_{\gamma_{\mathrm{D}}}\left(\gamma_{\mathrm{E}}\right)\right]\mathrm{d}\gamma_{\mathrm{E}}\\&=\underbrace{\int_0^{\infty}\ln\left(1+\gamma_{\mathrm{E}}\right)f_{\gamma_{\mathrm{E}}}\left(\gamma_{\mathrm{E}}\right)\mathrm{d}\gamma_{\mathrm{E}}}_{\Xi_1}\\&\quad-\underbrace{\int_0^{\infty}\ln\left(1+\gamma_{\mathrm{E}}\right)f_{\gamma_{\mathrm{E}}}\left(\gamma_{\mathrm{E}}\right)F_{\gamma_{\mathrm{D}}}\left(\gamma_{\mathrm{E}}\right)\mathrm{d}\gamma_{\mathrm{E}}}_{\Xi_2}.\end{aligned}\tag{45}$$

Using the integral Eq. (43), we can derive

$$\begin{aligned}\Xi_1&=\sum_{\Omega_{\mathrm{E}}}\int_0^{\infty}\ln\left(1+\gamma_{\mathrm{E}}\right)\exp\left(-\frac{\varsigma_{\mathrm{E}}}{\overline{\gamma}_{\mathrm{E}}}\gamma_{\mathrm{E}}\right)\mathrm{d}\gamma_{\mathrm{E}}\\&=\sum_{\Omega_{\mathrm{E}}}\Phi_1\left(\frac{\varsigma_{\mathrm{E}}}{\overline{\gamma}_{\mathrm{E}}}\right).\end{aligned}\tag{46}$$

Considering that the PDFs of γ_{D} and γ_{E} are similar, and that the expressions of $\overline{C}_{\mathrm{D\_SC}}$ and Ξ_2 have the same structure, we can rewrite Ξ_2 as

$$\Xi_2=\overline{C}_{\mathrm{D\_SC}}\left(N,M,\overline{\gamma}_{\mathrm{E}},\overline{\gamma}_{\mathrm{D}},\rho_{\mathrm{E}},\rho_{\mathrm{D}}\right).\tag{47}$$

The closed-form expression for $\overline{C}_{\mathrm{E\_SC}}$ is derived as

$$\begin{aligned}\overline{C}_{\mathrm{E\_SC}}=&\sum_{\Omega_{\mathrm{E}}}\Phi_1\left(\frac{\varsigma_{\mathrm{E}}}{\overline{\gamma}_{\mathrm{E}}}\right)\\&-\overline{C}_{\mathrm{D\_SC}}\left(N,M,\overline{\gamma}_{\mathrm{E}},\overline{\gamma}_{\mathrm{D}},\rho_{\mathrm{E}},\rho_{\mathrm{D}}\right).\end{aligned}\tag{48}$$

Finally, ESC can be obtained by substituting $\overline{C}_{\mathrm{D\_SC}}$ and $\overline{C}_{\mathrm{E\_SC}}$ into Eq. (13).

4.3 Asymptotic ergodic secrecy capacity of selection combining

In the scenario where $\gamma_{\mathrm{D}}\gg 1$, we have $\ln\left(1+\gamma_{\mathrm{D}}\right)\approx\ln\gamma_{\mathrm{D}}$. When $\overline{\gamma}_{\mathrm{D}}\to\infty$, we have $\overline{C}_{\mathrm{D}}^{\infty}$ as

$$\begin{aligned}&\overline{C}_{\mathrm{D}}^{\infty}\left(M,N,\overline{\gamma}_{\mathrm{D}},\overline{\gamma}_{\mathrm{E}},\rho_{\mathrm{D}},\rho_{\mathrm{E}}\right)\\&\quad=\int_0^{\infty}\ln\gamma_{\mathrm{D}}f_{\gamma_{\mathrm{D}}}\left(\gamma_{\mathrm{D}}\right)F_{\gamma_{\mathrm{E}}}\left(\gamma_{\mathrm{D}}\right)\mathrm{d}\gamma_{\mathrm{D}}.\end{aligned}\tag{49}$$

We consider the integral equation given by Eq. (4.352.1) in Gradshteyn and Ryzhik (2007):

$$\begin{aligned}\Phi_2\left(a\right)&=\int_0^{\infty}\ln\gamma_{\mathrm{D}}\exp\left(-a\gamma_{\mathrm{D}}\right)\mathrm{d}\gamma_{\mathrm{D}}\\&=-\frac{1}{a}\left(\ln a-\psi(1)\right),\end{aligned}\tag{50}$$

where $a>0$ and $\psi(\cdot)$ is the Digamma function (Gradshteyn and Ryzhik, 2007).

Using Eq. (50), we can derive

$$\begin{aligned}&\overline{C}_{\mathrm{D}}^{\infty}\left(M,N,\overline{\gamma}_{\mathrm{D}},\overline{\gamma}_{\mathrm{E}},\rho_{\mathrm{D}},\rho_{\mathrm{E}}\right)\\&=\sum_{\Omega_{\mathrm{D}}}\sum_{\Omega_{\mathrm{E}}}\frac{\overline{\gamma}_{\mathrm{E}}}{\varsigma_{\mathrm{E}}}\left[\Phi_2\left(\frac{\varsigma_{\mathrm{D}}}{\overline{\gamma}_{\mathrm{D}}}\right)-\Phi_2\left(\frac{\varsigma_{\mathrm{D}}}{\overline{\gamma}_{\mathrm{D}}}+\frac{\varsigma_{\mathrm{E}}}{\overline{\gamma}_{\mathrm{E}}}\right)\right].\end{aligned}\tag{51}$$

Considering $F_{\gamma_{\mathrm{D}}}(x)\approx 0$ when $\overline{\gamma}_{\mathrm{D}}\to\infty$ and $1-F_{\gamma_{\mathrm{D}}}\left(\gamma_{\mathrm{E}}\right)\approx 1$ given by Wang *et al.* (2014a; 2014b), we can write $\overline{C}_{\mathrm{E}}^{\infty}$ as

$$\begin{aligned}\overline{C}_{\mathrm{E}}^{\infty}&=\int_0^{\infty}\ln\left(1+\gamma_{\mathrm{E}}\right)f_{\gamma_{\mathrm{E}}}\left(\gamma_{\mathrm{E}}\right)\left[1-F_{\gamma_{\mathrm{D}}}\left(\gamma_{\mathrm{E}}\right)\right]\mathrm{d}\gamma_{\mathrm{E}}\\&=\int_0^{\infty}\ln\left(1+\gamma_{\mathrm{E}}\right)f_{\gamma_{\mathrm{E}}}\left(\gamma_{\mathrm{E}}\right)\mathrm{d}\gamma_{\mathrm{E}}=\sum_{\Omega_{\mathrm{E}}}\Phi_1\left(\frac{\varsigma_{\mathrm{E}}}{\overline{\gamma}_{\mathrm{E}}}\right).\end{aligned}\tag{52}$$

The closed-form expression for the asymptotic ESC of SC ($\overline{C}_{\mathrm{SC}}^{\infty}$) can be derived by substituting $\overline{C}_{\mathrm{D}}^{\infty}$ and $\overline{C}_{\mathrm{E}}^{\infty}$ into Eq. (13):

$$\overline{C}_{\mathrm{SC}}^{\infty}=\sum_{\Omega_{\mathrm{D}}}\sum_{\Omega_{\mathrm{E}}}\frac{\overline{\gamma}_{\mathrm{E}}}{\varsigma_{\mathrm{E}}}\left[\Phi_2\left(\frac{\varsigma_{\mathrm{D}}}{\overline{\gamma}_{\mathrm{D}}}\right)-\Phi_2\left(\frac{\varsigma_{\mathrm{D}}}{\overline{\gamma}_{\mathrm{D}}}+\frac{\varsigma_{\mathrm{E}}}{\overline{\gamma}_{\mathrm{E}}}\right)\right]-\sum_{\Omega_{\mathrm{E}}}\Phi_1\left(\frac{\varsigma_{\mathrm{E}}}{\overline{\gamma}_{\mathrm{E}}}\right),\tag{53}$$

where

$$\Phi_2\left(\frac{\varsigma_{\mathrm{D}}}{\overline{\gamma}_{\mathrm{D}}}\right)=-\frac{\overline{\gamma}_{\mathrm{D}}}{\varsigma_{\mathrm{D}}}\left[\ln\left(\frac{\varsigma_{\mathrm{D}}}{\overline{\gamma}_{\mathrm{D}}}\right)-\psi(1)\right],\tag{54}$$

$$\Phi_2\left(\frac{\varsigma_{\mathrm{D}}}{\overline{\gamma}_{\mathrm{D}}}+\frac{\varsigma_{\mathrm{E}}}{\overline{\gamma}_{\mathrm{E}}}\right)=-\left(\frac{\varsigma_{\mathrm{D}}}{\overline{\gamma}_{\mathrm{D}}}+\frac{\varsigma_{\mathrm{E}}}{\overline{\gamma}_{\mathrm{E}}}\right)^{-1}\cdot\left[\ln\left(\frac{\varsigma_{\mathrm{D}}}{\overline{\gamma}_{\mathrm{D}}}+\frac{\varsigma_{\mathrm{E}}}{\overline{\gamma}_{\mathrm{E}}}\right)-\psi(1)\right].\tag{55}$$

The asymptotic ESC of the SC scheme has the same form as Eq. (32), similar to that of the MRC scheme. When $\overline{\gamma}_{\mathrm{D}}\to\infty$, we have

$$\begin{aligned}&\lim_{\overline{\gamma}_{\mathrm{D}}\to\infty}\left[\Phi_2\left(\frac{\varsigma_{\mathrm{D}}}{\overline{\gamma}_{\mathrm{D}}}\right)-\Phi_2\left(\frac{\varsigma_{\mathrm{D}}}{\overline{\gamma}_{\mathrm{D}}}+\frac{\varsigma_{\mathrm{E}}}{\overline{\gamma}_{\mathrm{E}}}\right)\right]\\&=\lim_{\overline{\gamma}_{\mathrm{D}}\to\infty}\left[\Phi_2\left(\frac{\varsigma_{\mathrm{D}}}{\overline{\gamma}_{\mathrm{D}}}\right)-\Phi_2\left(\frac{\varsigma_{\mathrm{E}}}{\overline{\gamma}_{\mathrm{E}}}\right)\right]\\&=\lim_{\overline{\gamma}_{\mathrm{D}}\to\infty}-\frac{\overline{\gamma}_{\mathrm{D}}}{\varsigma_{\mathrm{D}}}\left[\ln\frac{\varsigma_{\mathrm{D}}}{\overline{\gamma}_{\mathrm{D}}}-\psi(1)\right]\\&=\lim_{\overline{\gamma}_{\mathrm{D}}\to\infty}\frac{\overline{\gamma}_{\mathrm{D}}}{\varsigma_{\mathrm{D}}}\left(\ln\overline{\gamma}_{\mathrm{D}}+\psi(1)-\ln\varsigma_{\mathrm{D}}\right).\end{aligned}\tag{56}$$

Considering Eqs. (56) and (53), we can derive Eqs. (57) and (58) (shown on the bottom of this page), where

$$\Sigma_{\Omega_{\mathrm{D1}}}=M\sum_{m_1=0}^{M-1}(-1)^{m_1}\binom{M-1}{m_1}\frac{1}{1-\rho_{\mathrm{D}}}\cdot\frac{1}{\alpha_{\mathrm{D}}},$$

and

$$\Sigma_{\Omega_{\mathrm{E1}}}=N\sum_{n_1=0}^{N-1}(-1)^{n_1}\binom{N-1}{n_1}\frac{1}{1-\rho_{\mathrm{E}}}\cdot\frac{1}{\alpha_{\mathrm{E}}}.$$

Further, by applying probability theory, we have

$$\begin{aligned}\int_0^{\infty}f_{\gamma_{\mathrm{D}}}(x)\,\mathrm{d}x&=\sum_{\Omega_{\mathrm{D}}}\int_0^{\infty}\exp\left(-\frac{\varsigma_{\mathrm{D}}}{\overline{\gamma}_{\mathrm{D}}}x\right)\mathrm{d}x\\&=\sum_{\Omega_{\mathrm{D}}}\frac{\overline{\gamma}_{\mathrm{D}}}{\varsigma_{\mathrm{D}}}=\sum_{\Omega_{\mathrm{D1}}}\frac{1}{\varsigma_{\mathrm{D}}}=1.\end{aligned}\tag{59}$$

$$\begin{aligned}S_{\infty}&=\lim_{\overline{\gamma}_{\mathrm{D}}\to\infty}\frac{\sum\limits_{\Omega_{\mathrm{D}}}\sum\limits_{\Omega_{\mathrm{E}}}\frac{\overline{\gamma}_{\mathrm{E}}}{\varsigma_{\mathrm{E}}}\left\{\Phi_2\left(\frac{\varsigma_{\mathrm{D}}}{\overline{\gamma}_{\mathrm{D}}}\right)-\Phi_2\left(\frac{\varsigma_{\mathrm{D}}}{\overline{\gamma}_{\mathrm{D}}}+\frac{\varsigma_{\mathrm{E}}}{\overline{\gamma}_{\mathrm{E}}}\right)\right\}-\sum\limits_{\Omega_{\mathrm{E}}}\Phi_1\left(\frac{\varsigma_{\mathrm{E}}}{\overline{\gamma}_{\mathrm{E}}}\right)}{\ln\overline{\gamma}_{\mathrm{D}}}\\&=\lim_{\overline{\gamma}_{\mathrm{D}}\to\infty}\frac{\sum\limits_{\Omega_{\mathrm{D1}}}\sum\limits_{\Omega_{\mathrm{E}}}\frac{\overline{\gamma}_{\mathrm{E}}}{\varsigma_{\mathrm{E}}\varsigma_{\mathrm{D}}}\left(\ln\overline{\gamma}_{\mathrm{D}}+\psi(1)-\ln\varsigma_{\mathrm{D}}\right)}{\ln\overline{\gamma}_{\mathrm{D}}}=\sum_{\Omega_{\mathrm{D1}}}\sum_{\Omega_{\mathrm{E1}}}\frac{1}{\varsigma_{\mathrm{E}}\varsigma_{\mathrm{D}}},\end{aligned}\tag{57}$$

$$\begin{aligned}\Omega_{\infty}&=\lim_{\overline{\gamma}_{\mathrm{D}}\to\infty}\left(\ln\overline{\gamma}_{\mathrm{D}}-\overline{C}_{SC}^{\infty}\right)=\lim_{\overline{\gamma}_{\mathrm{D}}\to\infty}\left(\ln\overline{\gamma}_{\mathrm{D}}-\overline{C}_{\mathrm{D}}^{\infty}+\overline{C}_{\mathrm{E}}^{\infty}\right)\\&=\lim_{\overline{\gamma}_{\mathrm{D}}\to\infty}\left\{\ln\overline{\gamma}_{\mathrm{D}}-\sum_{\Omega_{\mathrm{D1}}}\sum_{\Omega_{\mathrm{E}}}\frac{\overline{\gamma}_{\mathrm{E}}}{\varsigma_{\mathrm{E}}\varsigma_{\mathrm{D}}}[\ln\overline{\gamma}_{\mathrm{D}}+\psi(1)-\ln\varsigma_{\mathrm{D}}]+\overline{C}_{\mathrm{E}}^{\infty}\right\}\\&=-\sum_{\Omega_{\mathrm{D1}}}\sum_{\Omega_{\mathrm{E1}}}\frac{1}{\varsigma_{\mathrm{E}}\varsigma_{\mathrm{D}}}\psi(1)+\sum_{\Omega_{\mathrm{D1}}}\sum_{\Omega_{\mathrm{E1}}}\frac{1}{\varsigma_{\mathrm{D}}\varsigma_{\mathrm{E}}}\ln\overline{\varsigma}_{\mathrm{D}}+\overline{C}_{\mathrm{E}}^{\infty}.\end{aligned}\tag{58}$$

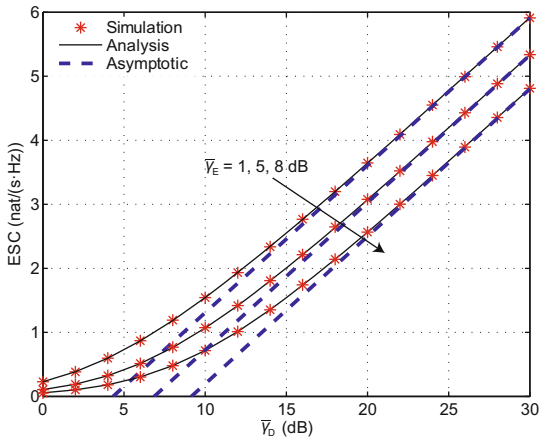

Fig. 1 ESC vs. $\overline{\gamma}_{\mathrm{D}}$ of MRC with weighting errors for $M = N = 2$, and $\rho_{\mathrm{D}} = \rho_{\mathrm{E}} = 0.5$

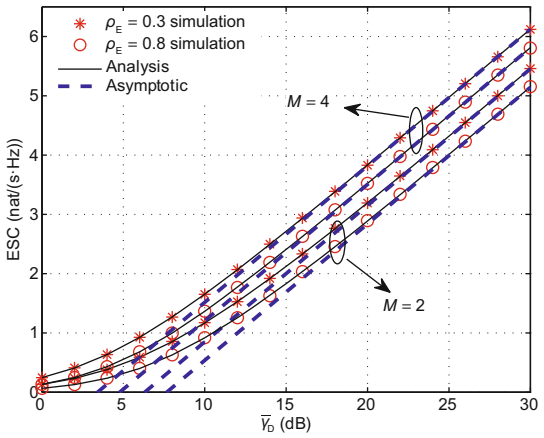

Fig. 2 ESC vs. $\overline{\gamma}_{\mathrm{D}}$ of MRC with weighting errors for $N = 2, \rho_{\mathrm{D}} = 0.5$, and $\overline{\gamma}_{\mathrm{E}} = 5$ dB

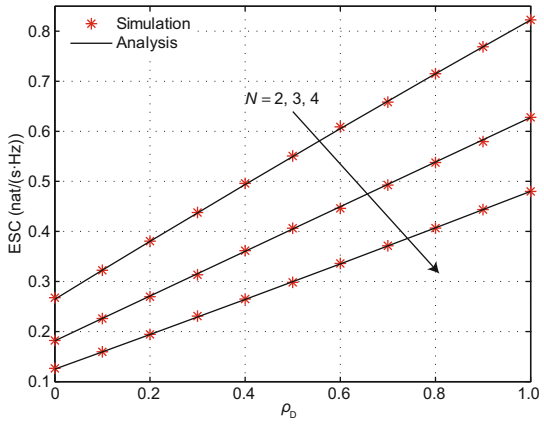

Fig. 3 ESC vs. ρ_{D} of MRC with weighting errors for $M = 3, \rho_{\mathrm{E}} = 0.5$, and $\overline{\gamma}_{\mathrm{D}} = \overline{\gamma}_{\mathrm{E}} = 5$ dB

Similarly, we can obtain $\sum\limits_{\Omega_{\mathrm{E1}}} \dfrac{1}{\varsigma_{\mathrm{E}}} = 1$.

Finally, we can achieve $S_\infty = 1$ and $\Omega_\infty = -\psi(1) + \sum\limits_{\Omega_{\mathrm{D1}}} \dfrac{1}{\varsigma_{\mathrm{D}}} \ln \varsigma_{\mathrm{D}} + \overline{C}_{\mathrm{E}}^{\infty}$.

5 Numerical results and discussions

5.1 Maximal ratio combining scheme

In this subsection, we run Monte-Carlo simulations to validate our exact and asymptotic expressions for ESC under the MRC scheme. In each simulation, S sends 10^5 bits to D. In MRC simulation, we can use Eq. (23) in Gans (1971) or Eq. (3) which reveals the correlation between the actual and estimated channels to build the SNR of the receivers.

Fig. 1 plots ESC vs. $\overline{\gamma}_{\mathrm{D}}$ for various $\overline{\gamma}_{\mathrm{E}}$'s over Rayleigh fading channels with weighting errors. It is evident that for a fixed $\overline{\gamma}_{\mathrm{E}}$, ESC increases with $\overline{\gamma}_{\mathrm{D}}$, as the channel state of the S–D link improves. It is shown that ESC can be improved when $\overline{\gamma}_{\mathrm{E}}$ degrades, because the channel state of the S–E link gets worse. Fig. 2 plots ESC vs. $\overline{\gamma}_{\mathrm{D}}$ for various M's and ρ_{E}'s. There is a pronounced decrease when ρ_{E} increases. This can be explained by the fact that the increasing ρ_{E} can improve the channel estimation at E. In addition, it is easy to observe that ESC can be improved when M increases, because of the increased MRC diversity gain at D.

It can be seen from Figs. 1 and 2 that the asymptotic ESC matches very well the simulation and the exact analytical results in the high $\overline{\gamma}_{\mathrm{D}}$ regime.

Fig. 3 plots ESC vs. ρ_{D} for various N's. It is clear that ESC increases with ρ_{D}. It is because increasing ρ_{D} can improve the channel estimation at D. One can also see that ESC decreases when N increases, because of the improved MRC diversity gain at E.

Further, it is obvious that simulation and analytical results match very well in Figs. 1–3.

5.2 Selection combining scheme

In this section, we run Monte-Carlo simulation to validate our exact and asymptotic expressions for ESC under the SC scheme. In each simulation, S sends 10^5 bits to D.

Fig. 4 indicates that ESC decreases when $\overline{\gamma}_{\mathrm{E}}$ increases, as the channel state of the S–E link, which degrades ESC, improves. Note that when $\overline{\gamma}_{\mathrm{D}}$ increases, the channel state of the S–D link improves. This explains why ESC increases with $\overline{\gamma}_{\mathrm{D}}$.

Fig. 5 illustrates the ESC of the SC scheme against $\overline{\gamma}_{\mathrm{D}}$ for various (M, N) combinations.

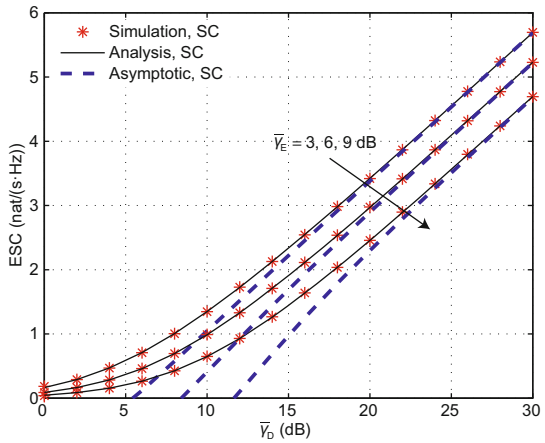

Fig. 4 ESC vs. $\overline{\gamma}_{\mathrm{D}}$ of SC with outdated CSI for $M = 3, N = 2, \rho_{\mathrm{D}} = 0.5, \rho_{\mathrm{E}} = 0.6, N_0 = 1$, and $P_{\mathrm{S}} = 3$ dB

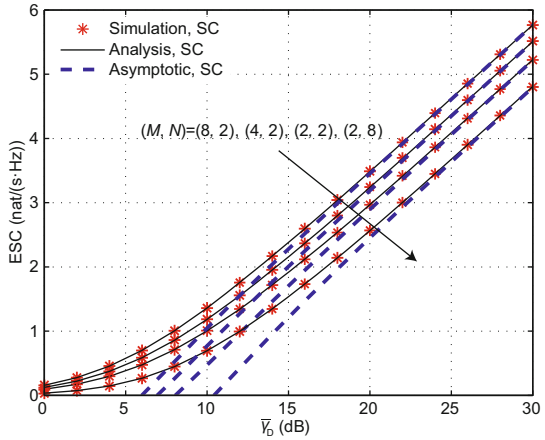

Fig. 5 ESC vs. $\overline{\gamma}_{\mathrm{D}}$ of SC with outdated CSI for $\overline{\gamma}_{\mathrm{E}} = 5$ dB, $\rho_{\mathrm{D}} = 0.5, \rho_{\mathrm{E}} = 0.6, N_0 = 1$, and $P_{\mathrm{S}} = 3$ dB

Obviously, there is an upward trend in ESC when M increases and N decreases, because the diversity gain of D increases and that of E decreases.

In addition, Figs. 4 and 5 show that our asymptotic ESC matches the analysis and simulation very well in the high $\overline{\gamma}_{\mathrm{D}}$ regime, proving the accuracy of our derivations. Further, it is clear that $-\Omega_\infty$ of SC increases when M increases and N and $\overline{\gamma}_{\mathrm{E}}$ decrease. Ω_∞ and S_∞ are independent of $\overline{\gamma}_{\mathrm{D}}$. The reason can be explained by Eqs. (57) and (58).

Fig. 6 compares the secrecy performance of the SC and MRC schemes for various ρ_{E}'s. In the scenario with a fixed ρ_{E}, we can observe that the ESC of the MRC scheme outperforms the one of the SC scheme in the high ρ_{D} region. There is a cutoff, at about $\rho_{\mathrm{D}} = 0.15$, of the lines for the MRC and SC schemes when $\rho_{\mathrm{E}} = 0.4$.

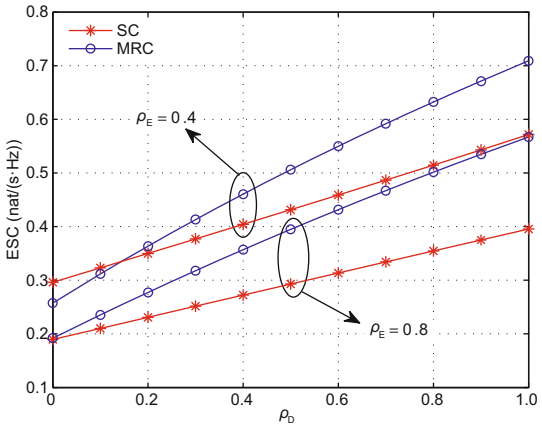

Fig. 6 ESC vs. ρ_{D} of MRC with weighting errors/SC with outdated CSI for $M = N = 3, \overline{\gamma}_{\mathrm{D}} = \overline{\gamma}_{\mathrm{E}} = 5$ dB, $N_0 = 1$, and $P_{\mathrm{S}} = 1$ dB

6 Conclusions

In this paper, we have analyzed the ESC of the MRC/SC scheme in SIMO wiretap systems over Rayleigh fading channels with imperfect CSI. The exact and asymptotic closed-form expressions for ESC have been derived and verified through simulations. Further, the high SNR slope and high SNR power offset predict ESC accurately in the high SNR region.

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Appendix: Derivation of the closed-form expressions for I_4 and I_5

Substituting the PDF of γ_{D} into I_4, we can obtain

$$I_4=\sum_{i=1}^{M}A\left(i\right)\frac{1}{\Gamma(i)\overline{\gamma}_{\mathrm{D}}^{i}}\int_0^{\infty}\gamma_{\mathrm{D}}^{i-1}\cdot\exp\left(-\frac{\gamma_{\mathrm{D}}}{\overline{\gamma}_{\mathrm{D}}}\right)\cdot\ln\gamma_{\mathrm{D}}\,\mathrm{d}\gamma_{\mathrm{D}}. \tag{A1}$$

By using Eq. (4.352.1) in Gradshteyn and Ryzhik (2007) and after some manipulations, we have

$$I_4=\sum_{i=1}^{M}A(i)\left[\psi(i)+\ln\overline{\gamma}_D\right], \tag{A2}$$

where $\psi(\cdot)$ is the Digamma function (Gradshteyn and Ryzhik, 2007).

Substituting $\chi_{\gamma_{\mathrm{E}}}\left(\gamma_{\mathrm{E}}\right)$ into I_5, we have

$$I_5=\sum_{j=1}^{N}B(j)\sum_{m=0}^{j-1}\frac{1}{m!\overline{\gamma}_{\mathrm{E}}^{m}}\int_0^{\infty}\frac{\gamma_{\mathrm{E}}^{m}}{1+\gamma_{\mathrm{E}}}\cdot\exp\left(-\frac{\gamma_{\mathrm{E}}}{\overline{\gamma}_{\mathrm{E}}}\right)\mathrm{d}\gamma_{\mathrm{E}}. \tag{A3}$$

By using Eq. (3.353.5) in Gradshteyn and Ryzhik (2007) and after some manipulations, we can obtain the closed-form expression for I_5 as

$$I_5=\sum_{j=1}^{N}B(j)\sum_{m=0}^{j-1}\frac{1}{m!\overline{\gamma}_{\mathrm{E}}^{m}}\cdot\left[(-1)^{m-1}\exp\left(\frac{1}{\overline{\gamma}_{\mathrm{E}}}\right)\mathrm{Ei}\left(-\frac{1}{\overline{\gamma}_{\mathrm{E}}}\right)+\sum_{k=1}^{m}(k-1)!\overline{\gamma}_{\mathrm{E}}^{k}(-1)^{m-k}\right], \tag{A4}$$

where $\mathrm{Ei}(\cdot)$ is the exponential integral function (Gradshteyn and Ryzhik, 2007).