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Research Article

Performance Analysis of Secrecy Outage Probability for AF-Based Partial Relay Selection with Outdated Channel Estimates

Kyu-Sung Hwang

Department of Electronic Engineering, Kyungil University, Gyeongbuk, Republic of Korea

Correspondence should be addressed to Kyu-Sung Hwang; kshwang@kiu.ac.kr

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We study the secrecy outage probability of the amplify-and-forward (AF) relaying protocol, which consists of one source, one destination, multiple relays, and multiple eavesdroppers. In this system, the aim is to transmit the confidential messages from a source to a destination via the selected relay in presence of eavesdroppers. Moreover, partial relay selection scheme is utilized for relay selection based on outdated channel state information where only neighboring channel information (source-relays) is available and passive eavesdroppers are considered where a transmitter does not have any knowledge of eavesdroppers' channels. Specifically, we offer the exact secrecy outage probability of the proposed system in a one-integral form as well as providing the asymptotic secrecy outage probability in a closed-form. Numerical examples are given to verify our provided analytical results for different system conditions.

1. Introduction

Due to the broadcast nature of wireless communications, the security issues have received a lot of attention as a variety of wireless communications increases, where wireless medium is allowed to be susceptible of eavesdropping without evidences. While the traditional security based on cryptography is performed in the upper layers (e.g., network layer), the *information-theoretic* approach [1, 2] is utilized to strengthen the security of wireless communications in the physical layer. There are some pioneering works [1–5] on physical layer security based on a wiretap channel consisting of a source (Alice), a destination (Bob), and an eavesdropper (Eve) where the *perfect secrecy* can be achieved without the help of cryptography when the difference between the capacities of main and eavesdropper channels keeps positive.

Recently, relay communications (or cooperative communications) have been considered as an efficient technique to attain broader coverage and to overcome channel impairments [6, 7]. Moreover, the information-theoretic security with relay communications in the presence of eavesdroppers has been investigated in the previous works [8–12]. Specifically, authors in [8] introduced the relay-eavesdropper channel and offered an outer bound on the rate-equivocation region over several cooperation strategies. Dong et al. in [9] investigated the optimal relay weights to maximize the achievable secrecy rate for the multiple relays employing several relay protocols. Krikidis in [10] dealt with opportunistic relay selection of the decode-and-forward- (DF-) based cooperative network and provided the secrecy outage probability (SOP) while the authors in [11] proposed relay selection strategies of the DF-based cooperative network to the capacity to the destination and to minimize that to the eavesdroppers. In [12], authors analyzed the SOP of the amplify-and-forward (AF) transmission with a multiantenna relay where some diversity techniques are considered at the relay. Moreover, because of the increasing demand and importance of secure communications, some pioneering works on physical layer security with relay communications are summarized in the previous researches [13, 14].

In the previous works [10, 11], relay selection is performed based on all the channel state information (CSI) of both the destination and the eavesdropper. However, from a practical point of view, mandating the CSI knowledge of the eavesdroppers' channels leads a controversial subject, so passive eavesdropping can be suited for a practical case, where no CSI of the eavesdropper's channel is available at a transmitter [15]. Moreover, since centralized approaches require a lot of channel feedback information from all the links, partial relay selection [16] can be suited more for a physical layer security. In addition, it is well known that relay selection in a distributed network is very time sensitive; thus outdated CSI due to feedback delay leads a crucial issue for practical relay transmission [17–19]. To the best of our knowledge, however, there has been no work on SOP analysis for the AF relaying transmission with partial relay selection based on outdated CSI.

Motivated by this, in this paper, we analyze the SOP of the AF relaying transmission in the presence of passive eavesdroppers. In addition, we adopt the partial relay selection [16] which uses the partial information that relay selection follows only the best channel between the source and the relays and undergoes outdated CSI. It is worth noting that the proposed scheme does not require any knowledge for the CSI from the destination and the eavesdroppers. In this paper, we fill this gap and study the SOP analysis of the AF-based partial relay selection with outdated CSI. The contributions of this paper are summarized in what follows:

(i) We summarize the secrecy capacity of the AF-based partial relay selection with outdated CSI and multiple eavesdroppers.

(ii) We provide the exact SOP of the proposed AF-based partial relay selection scheme in a one-integral form as well as derive the asymptotic SOP in a closed-form.

(iii) We verify our analytical results with some selected computer-based simulation results.

The rest of this paper is organized as follows. Section 2 introduces the system description of this work, partial relay selection with outdated CSI. Section 3 investigates a physical layer security in terms of the secrecy capacity for partial relay selection with outdated CSI. Section 4 provides the exact and asymptotic performance analyses of SOP for the proposed partial relay selection system. Finally, some selected numerical examples are shown and discussed in Section 5 before some conclusions are drawn in Section 6.

Notation. Throughout this paper, $\overline{F}_X(\cdot)$ and $f_X(\cdot)$ denote a complementary cumulative distribution function (CCDF) and a probability density function (PDF) of a random variable X, respectively. $x \sim \mathscr{CN}(\mu,\sigma^2)$ denotes a circular symmetric complex Gaussian random variable x with mean μ and variance σ^2. $E[\cdot]$ is an expectation operator.

2. System Description

2.1. System Model. As shown in Figure 1, we consider a two-hop-based cooperative network consisting of one source, one destination, L relays, and N passive eavesdroppers denoted by S, D, R_i for $i = 1,\ldots,L$, and E_j for $j = 1,\ldots,N$, respectively. We denote h_{R_i}, h_{D_i}, and $h_{E_{ij}}$ as channel coefficients for the S-R_i, R_i-D, and R_i-E_j links, respectively. Specifically, the

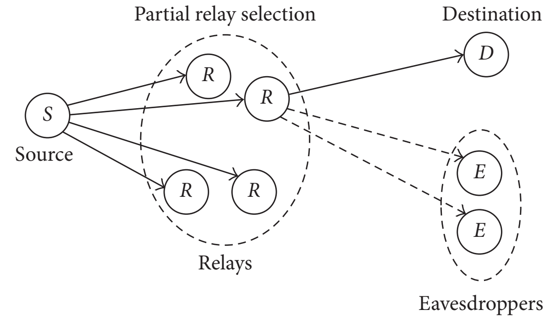

Figure 1: Illustration of system model.

independent identically distributed (i.i.d.) channel condition per link is considered where $h_{R_i} = \mathscr{CN}(0,\Omega_1)$, $h_{D_i} = \mathscr{CN}(0,\Omega_2)$, and $h_{E_{ij}} = \mathscr{CN}(0,\Omega_3)$. In this work, it is assumed that the eavesdroppers are also legitimate users in the network who are not allowed to receive the particular signals and do not cooperate or collude with each other. In addition, since the secrecy channel capacity is a theoretical bound which can be used for robust system design, it is assumed that the knowledge of the average signal-to-noise ratio between the relays and the passive eavesdroppers is available. We also assume that each terminal operates in a half-duplex transmission which requires two time slots and AF protocol is applied at the relay. In addition, there is no direct link between the source and the destination. During the first time slot, the source transmits its signal to the selected relay by the partial relay selection. The selected relay amplifies its received signal and then forwards it to the destination in the second time slot. The received signals at the relay and at the destination can be, respectively, represented by

$$y_{R_k} = \sqrt{\mathscr{E}_S} h_{R_k} x + n_{R_k}, \tag{1}$$

$$y_D = \sqrt{\mathscr{E}_S}\sqrt{\mathscr{E}_{R_k}}\beta_k h_{R_k} h_{D_k} x + \sqrt{\mathscr{E}_{R_k}}\beta_k h_{D_k} n_{R_k} + n_D, \tag{2}$$

where x is the transmitted signal with $E[|x|^2] = 1$, $\sqrt{\mathscr{E}_S}$ and $\sqrt{\mathscr{E}_{R_k}}$ are the transmission powers at S and R_k, respectively, and n_{R_k} and n_D are the additive white Gaussian noise (AWGN) with $n_{R_k} \sim \mathscr{CN}(0,N_0)$ and $n_D \sim \mathscr{CN}(0,N_0)$, respectively. In (1) and (2), the subscript k denotes the selected relay by the partial relay selection as $k = \arg\max_i(|h_{R_i}|^2/N_0)$ and β_k denotes the variable amplifying gain as $\beta_k = 1/\sqrt{\mathscr{E}_S|h_{R_k}|^2 + N_0}$.

In the wiretapper channel between the selected relay k and the eavesdroppers, we consider passive eavesdroppers where no CSI feedback is available. Therefore, the eavesdropper just overhears the information conveyed from the selection relay k to the destination [15]. Finally, the received signal at the jth eavesdropper can be written as

$$y_E = \sqrt{\mathscr{E}_S}\sqrt{\mathscr{E}_{R_k}}\beta_k h_{R_k} h_{E_{kj}} x + \sqrt{\mathscr{E}_{R_k}}\beta_k h_{E_{kj}} n_{R_k} + n_{E_j}, \tag{3}$$

where n_{E_j} is also AWGN with $n_{E_j} \sim \mathscr{CN}(0,N_0)$.

2.2. Partial Relay Selection with Outdated CSI. In this work, we assume that the system with partial relay selection suffers from outdated CSI due to, for example, a feedback delay T_d while selecting the best relay according to the channels between the source and the relays. Thus, the selected best relay is not based on a current time instant which leads to some performance losses. Hereafter, we denote the outdated channel coefficient between nodes S and R_i as $\tilde{h}_{R_i} = \rho h_{R_i} + (\sqrt{1-\rho^2})e_{R_i}$ where e_{R_i} is a circular symmetric complex Gaussian random variable with a zero mean and the variable of Ω_1, and the correlation coefficient ρ for $0 \le \rho \le 1$ describes an impact of outdated CSI between h_{R_i} and $\tilde{h}_{R_i}$ given by $\rho = J_0(2\pi f_d T_d)$. $J_0(\cdot)$ and f_d denote the zero-order Bessel function of the first kind [20, Eq. (8.411)] and the maximum Doppler frequency of h_{R_i}, respectively.

From (2) and (3) with the outdated channel coefficients $\tilde{h}_{R_i}$, it can be shown that the instantaneous output signal-to-noise ratios (SNRs) at the destination and at the eavesdroppers j via the selected relay k by partial relay selection can be obtained as follows [17]:

$$\tilde{\gamma}_{SD} = \frac{\tilde{\gamma}_{h_{R_k}} \gamma_{h_{D_k}}}{\tilde{\gamma}_{h_{R_k}} + \gamma_{h_{D_k}} + 1}, \tag{4}$$

$$\tilde{\gamma}_{SE_j} = \frac{\tilde{\gamma}_{h_{R_k}} \gamma_{h_{E_{kj}}}}{\tilde{\gamma}_{h_{R_k}} + \gamma_{h_{E_{kj}}} + 1}, \tag{5}$$

respectively, where $\tilde{\gamma}_{h_{R_k}} = \mathscr{E}_S |\tilde{h}_{R_k}|^2 / N_0$ and $\gamma_{h_A} = \mathscr{E}_A |h_A|^2 / N_0$.

In order to treat (4) and (5), it is required to know the statistics of $\tilde{\gamma}_{h_{R_k}}$. According to the theory of concomitants of order statistics, the PDF of the outdated SNR $\tilde{\gamma}_{h_{R_k}}$, $f_{\tilde{\gamma}_{h_{R_k}}}(\cdot)$, is evaluated by the following [21]:

$$f_{\tilde{\gamma}_{h_{R_k}}}(x) = \int_0^\infty f_{\tilde{\gamma}_{h_{R_k}} \mid \gamma_{h_{R_k}}}(x \mid y) f_{\gamma_{h_{R_k}}}(y)\, dy, \tag{6}$$

where $f_{\tilde{\gamma}_{h_{R_k}} \mid \gamma_{h_{R_k}}}(x \mid y) = f_{\tilde{\gamma}_{h_{R_k}}, \gamma_{h_{R_k}}}(x, y) / f_{\gamma_{h_{R_k}}}(y)$ is the PDF of $\tilde{\gamma}_{h_{R_k}}$ conditioned on $\gamma_{h_{R_k}}$. Since $\tilde{\gamma}_{h_{R_k}}$ and $\gamma_{h_{R_k}}$ are two correlated exponentially distribution random variables, the joint PDF of $\tilde{\gamma}_{h_{R_k}}$ and $\gamma_{h_{R_k}}$ is given by

$$\begin{aligned} f_{\tilde{\gamma}_{h_{R_k}}, \gamma_{h_{R_k}}}(x, y) \\ = \frac{\exp\left(-(x+y)/(1-\rho)\Omega_1\right)}{(1-\rho)\Omega_1^2} I_0\left(\frac{2\sqrt{\rho x y}}{(1-\rho)\Omega_1}\right), \end{aligned} \tag{7}$$

where $I_0(x)$ is the modified Bessel function of the first kind. By substituting PDF $f_{\gamma_{h_{R_k}}}(y)$ into (6) where $f_{\gamma_{h_{R_k}}}(y) = L(\exp(-y/\Omega_1)/\Omega_1)(1 - \exp(-y/\Omega_1))^{L-1}$ and applying the binomial expansion $(1+z)^L = \sum_{n=0}^{L} \binom{L}{n} z^n$, the PDF of $\tilde{\gamma}_{h_{R_k}}$ for partial relay selection with outdated CSI over the i.i.d. Rayleigh fading channels is finally given by the following [17, Eq. (9)]:

$$\begin{aligned} f_{\tilde{\gamma}_{h_{R_k}}}(x) = k \binom{L}{k} \sum_{m=0}^{k-1} \frac{(-1)^m \binom{k-1}{m}}{\left((L-k+m)(1-\rho)+1\right)\Omega_1} \\ \times \exp\left(-\frac{(L-k+m+1)\,x}{\left((L-k+m)(1-\rho)+1\right)\Omega_1}\right). \end{aligned} \tag{8}$$

3. Secrecy Capacity with Partial Relay Selection

In this paper, we assume that all the channels are quasistatic fading channels which implies the fading coefficients are invariant during the transmission of an entire codeword. In addition, the codeword is enough long to satisfy the required secrecy capacity in every transmission. Under these assumptions, the achievable secrecy capacity C_s is given by the following [5]:

$$C_s = \left[C_m - C_e\right]^+, \tag{9}$$

where $[A]^+$ denotes $\max(A, 0)$. In (9), $C_m = (1/2)\log_2(1+\tilde{\gamma}_{SD})$ and $C_e = (1/2)\log_2(1 + \max_j(\tilde{\gamma}_{SE_j}))$ denote the capacity of the main channel between the source and the destination via the selected relay and of the eavesdropper channel between the source and the eavesdropper channel via the selected relay, respectively. In the eavesdropper channel, it is reasonable to consider the worst case of eavesdroppers for the secrecy capacity which has the maximum capacity at eavesdroppers. Thus, in (9), $\max_j(\gamma_{SE_j})$ can be treated as $\max_j(\tilde{\gamma}_{h_{R_k}} \gamma_{h_{E_{kj}}} / (\tilde{\gamma}_{h_{R_k}} + \gamma_{h_{E_{kj}}} + 1)) = \tilde{\gamma}_{h_{R_k}} \gamma_{h_{E_{kl}}} / (\tilde{\gamma}_{h_{R_k}} + \gamma_{h_{E_{kl}}} + 1)$ for the fixed value $\gamma_{h_{R_k}}$ where $l = \arg\max_j(|h_{E_{jk}}|^2/N_0)$ because it is a monotonic increasing function. Finally, the achievable secrecy capacity C_s can be finally represented as

$$C_s = \left[\frac{1}{2}\log_2\left(\frac{1 + \tilde{\gamma}_{h_{R_k}} \gamma_{h_{D_k}} / \left(\tilde{\gamma}_{h_{R_k}} + \gamma_{h_{D_k}} + 1\right)}{1 + \tilde{\gamma}_{h_{R_k}} \gamma_{h_{E_{kl}}} / \left(\tilde{\gamma}_{h_{R_k}} + \gamma_{h_{E_{kl}}} + 1\right)}\right)\right]^+. \tag{10}$$

Since the two hops of the proposed system are independent, we can write the PDFs of $\gamma_{h_{D_k}}$ and of $\gamma_{h_{E_k}}$ as $f_{\gamma_{h_{D_k}}}(x) = \exp(-x/\Omega_2)/\Omega_2$ and $f_{\gamma_{h_{E_{kl}}}}(x) = N(\exp(-x/\Omega_3)/\Omega_3)(1 - \exp(-x/\Omega_3))^{N-1}$, respectively.

4. Performance Analysis of Secrecy Outage Probability with Partial Relay Selection

In this section, we analyze the SOP of the AF-based partial relay selection in presence of eavesdroppers. Furthermore, we derive the exact SOP in a one-integral form as well as the asymptotic SOP in a closed-form for high average SNRs. In this work, we consider that the secrecy outage event occurs when the achievable secrecy capacity C_s is below the target secrecy capacity C_t as follows [5]:

$$P_{\text{out}}(C_t) = \Pr\left[C_s < C_t\right]. \tag{11}$$

Equation (11) can be rewritten as

$$P_{\text{out}}(C_t) = \Pr\left[\frac{1+\tilde{\gamma}_{h_{R_k}}\gamma_{h_{D_k}}/\left(\tilde{\gamma}_{h_{R_k}}+\gamma_{h_{D_k}}+1\right)}{1+\tilde{\gamma}_{h_{R_k}}\gamma_{h_{E_{kl}}}/\left(\tilde{\gamma}_{h_{R_k}}+\gamma_{h_{E_{kl}}}+1\right)} < T\right], \quad (12)$$

where $T = 2^{2C_t}$. In the following theorem, we obtain the exact SOP of the proposed system.

Theorem 1. *The exact SOP of the AF-based partial relay selection in presence of eavesdroppers with outdated CSI can be obtained in a one-integral form as*

$$P_{out}(C_t) = \int_0^\infty \mathcal{I}(z)\, f_{\gamma_{h_{E_{kl}}}}(z)\, dz, \quad (13)$$

where

$$\begin{aligned}\mathcal{I}(z) &= 1 - 2k\binom{L}{k}\sum_{m=0}^{k-1}\frac{(-1)^m\binom{k-1}{m}(z+1)}{((L-k+m)(1-\rho)+1)} \\ &\times \sqrt{\frac{T(T-1)}{\mathcal{B}(k,m)\,\Omega_1\Omega_2}}\exp\left(-\left(\frac{T(z+1)-1}{\Omega_2}\right.\right. \\ &\left.\left.+\frac{(T-1)(z+1)\mathcal{B}(k,m)}{\Omega_1}\right)\right)\times K_1\left(2(z+1)\right. \\ &\left.\cdot\sqrt{\frac{T(T-1)\mathcal{B}(k,m)}{\Omega_1\Omega_2}}\right)\end{aligned} \quad (14)$$

and K_v is the modified Bessel function of the second kind with order v.

Proof. See Appendix. □

For the case of $\rho = 1$ which corresponds to the partial relay selection with perfect channel estimates (i.e., $k = L$), (14) can be simplified as

$$\begin{aligned}\mathcal{I}(z) &= 1 - 2L\sum_{i=1}^{L}(-1)^{i+1}\binom{L-1}{i-1}(z+1)\sqrt{\frac{T(T-1)}{i\Omega_1\Omega_2}} \\ &\times\exp\left(-\left(\frac{(T-1)(z+1)i}{\Omega_1}+\frac{T(z+1)-1}{\Omega_2}\right)\right) \\ &\times K_1\left(2(z+1)\sqrt{\frac{T(T-1)i}{\Omega_1\Omega_2}}\right).\end{aligned} \quad (15)$$

Lemma 2. *The asymptotic SOP of the AF-based partial relay selection with eavesdroppers can be obtained with the help of the approximation $K_1(x) \approx 1/x$ for large x as*

$$\begin{aligned}P_{out}^{asy}(C_t) &= 1 - \frac{kN}{\Omega_3} \\ &\cdot\binom{L}{k}\sum_{m=0}^{k-1}\sum_{j=1}^{N}\frac{(-1)^m(-1)^{j+1}\binom{k-1}{m}\binom{N-1}{j-1}}{((L-k+m)(1-\rho)+1)\mathcal{B}(k,m)} \\ &\times\left(\frac{\mathcal{B}(k,m)(T-1)}{\Omega_1}+\frac{T}{\Omega_2}+\frac{j}{\Omega_3}\right)^{-1} \\ &\times\exp\left(-\left(\frac{\mathcal{B}(k,m)(T-1)}{\Omega_1}+\frac{T-1}{\Omega_2}\right)\right).\end{aligned} \quad (16)$$

In case of $\rho = 1$, (16) can be simplified as

$$\begin{aligned}P_{out}^{asy}(C_t) &= 1 - LN\sum_{i=1}^{L}\sum_{j=1}^{N}\frac{(-1)^{i+1}(-1)^{j+1}}{i\Omega_3}\binom{L-1}{i-1}\binom{N-1}{j-1} \\ &\times\left(\frac{(T-1)i}{\Omega_1}+\frac{T}{\Omega_2}+\frac{j}{\Omega_3}\right)^{-1} \\ &\times\exp\left(-\left(\frac{(T-1)i}{\Omega_1}+\frac{T-1}{\Omega_2}\right)\right).\end{aligned} \quad (17)$$

For one eavesdropper case with $\rho = 1$, (17) can be fully simplified as

$$\begin{aligned}P_{out}^{asy}(C_t) &= 1 \\ &- L\sum_{i=1}^{L}\frac{(-1)^{i+1}}{i\Omega_3}\binom{L-1}{i-1}\left(\frac{i(T-1)}{\Omega_1}+\frac{T}{\Omega_2}+\frac{1}{\Omega_3}\right)^{-1} \\ &\times\exp\left(-\left(\frac{(T-1)i}{\Omega_1}+\frac{T-1}{\Omega_2}\right)\right).\end{aligned} \quad (18)$$

5. Numerical Examples

In this section, we evaluate the SOP of the proposed AF-based partial relay selection scheme over i.i.d. Rayleigh fading channels by Monte-Carlo simulations and compare them with our analysis in (13) and (16).

In Figures 2–5, we set $\mathcal{E} = \mathcal{E}_S = \mathcal{E}_{R_i}$, $8\Omega_1 = \Omega_2$, and $C_t = 1$ bps/Hz where the average SNR is defined as $\mathcal{E}/N_0$. Figure 2 illustrates the SOP of the AF-based partial relay selection with the different number of relays $L = 1, 2, 6$ in the perfect CSI condition. In this example, we observe that the considered partial relay selection scheme improves the SOP performance with one relay case ($L = 1$), but the performance gain with the large number of relays is limited in the high SNR region which behavior is also the same as the conventional partial relay selection without eavesdroppers. In addition, as far as the asymptotic result in (16) is concerned, the performance results in the high SNRs are almost the same regardless of the number of relays (for $L \geq 2$) and the results in the low SNRs

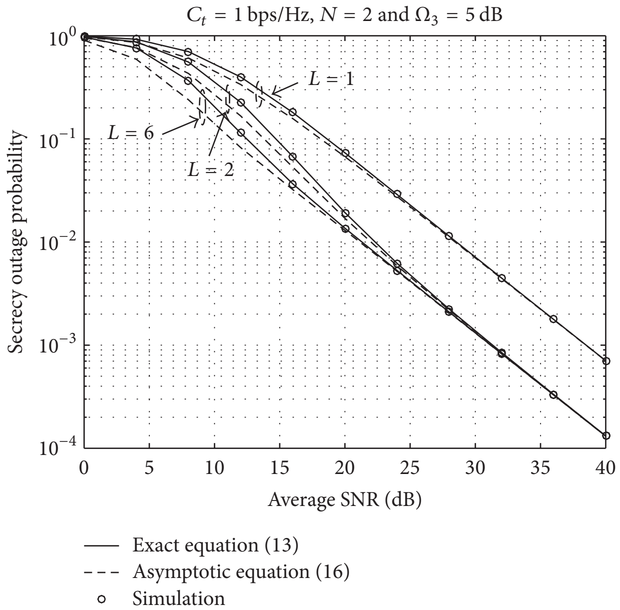

FIGURE 2: Secrecy outage probability against the average SNR of the AF-based partial relay selection scheme with different number of relays $L = 1, 2, 6$.

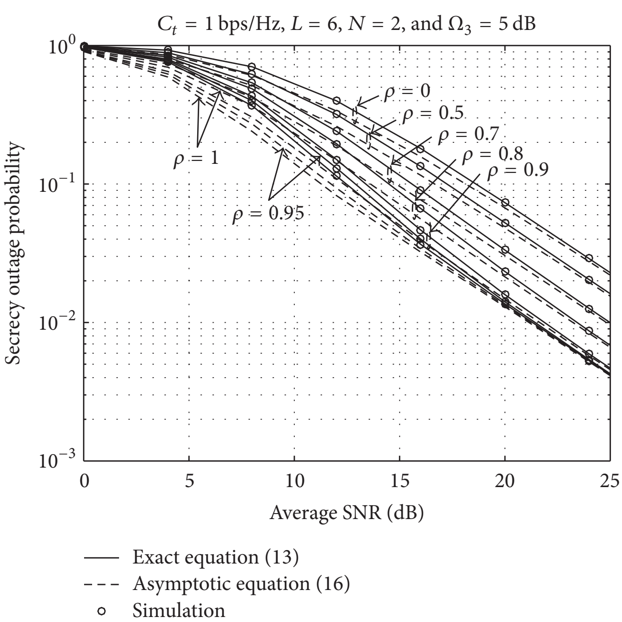

FIGURE 3: Secrecy outage probability against the average SNR of the AF-based partial relay selection scheme with different channel correlation coefficients $\rho = 0, 0.5, 0.7, 0.8, 0.9, 0.95, 1$.

can be useful for a reliable lower-bounds. In Figure 3, it can be seen that the SOP increases as the correlation coefficient decreases; for example, the cases of $\rho = 0$ and $\rho = 1$ correspond to the cases of $L = 1$ and $L = 6$, respectively. We also observe that our provided analyses using (14) are well matched with the simulation results and the asymptotic result in (16) has a good agreement as a lower-bound.

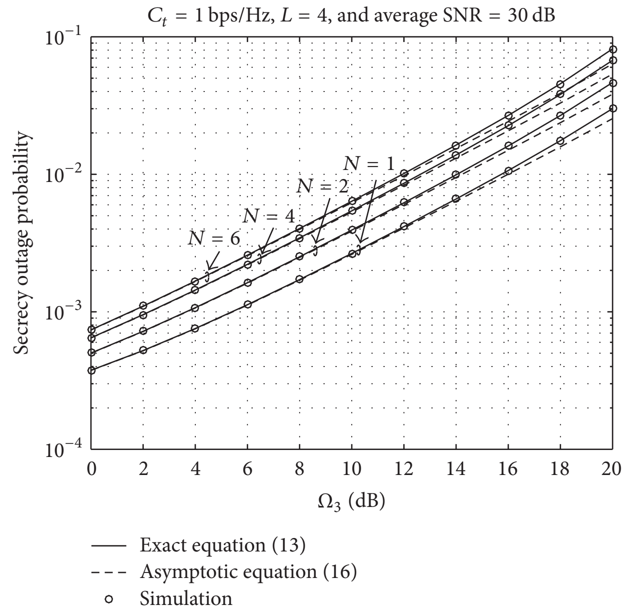

FIGURE 4: Secrecy outage probability against the average eavesdroppers' SNR of the AF-based partial relay selection scheme with different number of eavesdroppers $N = 1, 2, 4, 6$.

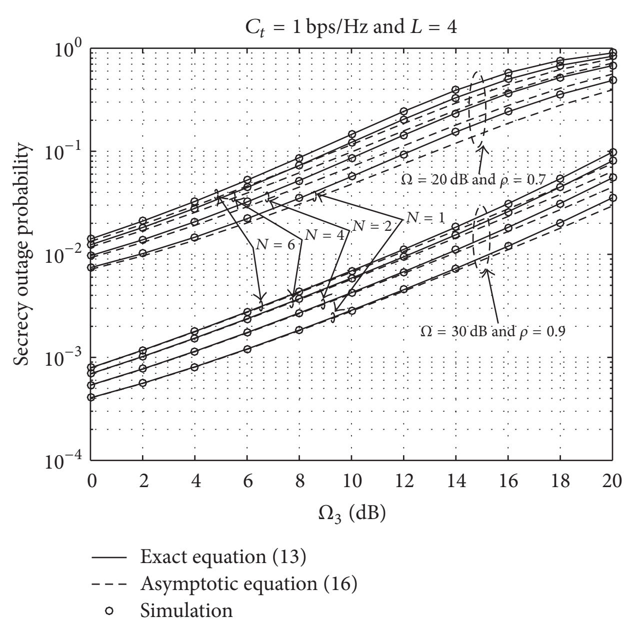

FIGURE 5: Secrecy outage probability against the average eavesdroppers' SNR of the AF-based partial relay selection scheme with different number of eavesdroppers $N = 1, 2, 4, 6$ and different channel correlation coefficients $\rho = 0.7, 0.9$.

As shown in Figures 4 and 5, the SOP performance decreases as the gain of relay-eavesdropper channels and the number of eavesdroppers increase. In addition, we also check the impact on outdated CSI for the AF-based partial relay selection system with different number of eavesdroppers and verify our analytical results for the exact and asymptotic

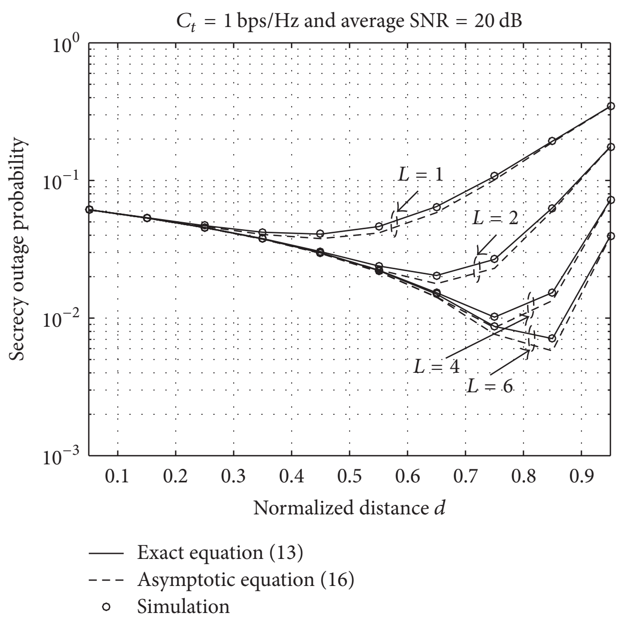

FIGURE 6: Secrecy outage probability against the normalized distance d of the AF-based partial relay selection scheme with different number of relays $L = 1, 2, 4, 6$.

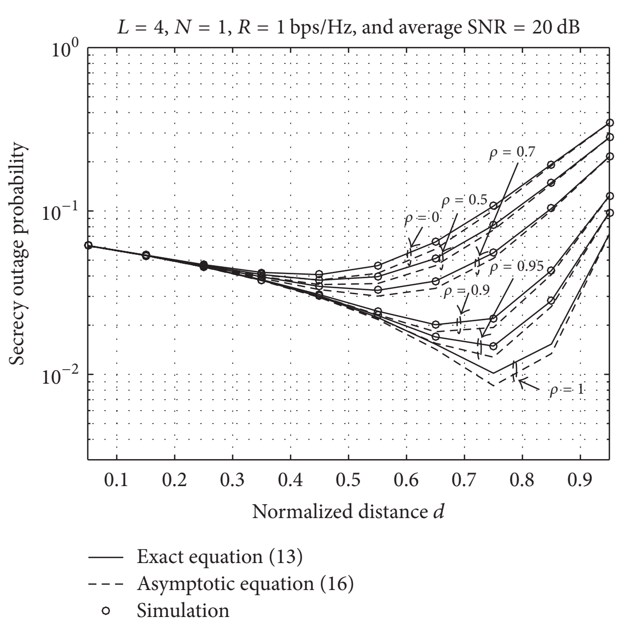

FIGURE 7: Secrecy outage probability against the normalized distance d of the AF-based partial relay selection scheme with different channel correlation coefficients $\rho = 0, 0.5, 0.7, 0.9, 0.95, 1$.

expression are in a good agreement with the computer simulations.

Figures 6 and 7 show the SOP of the considered partial relay selection system with parameters $\Omega_1 = d^{-3}\mathscr{E}/N_0$, $\Omega_2 = (1-d)^{-3}\mathscr{E}/N_0$, and $\Omega_3 = .1(1.5-d)^{-3}\mathscr{E}/N_0$, where d is a normalized distance, distance of $S-R$ over distance of $S-D$. In these examples, we observe that the performance gain by the partial relay selection is rarely obtained when the relays are placed near the source. This is because the performance of two-hop relay transmission is dominated by worse one. In such a case, the SOP performance follows the conventional scheme since it is affected by only the difference between the capacities of $R-D$ and $R-E$ channels. Moreover, the impact on outdated CSI is also observed in Figure 7 with different channel correlation coefficients and it can be seen that our analytical results in (13) and (16) are in a good agreement with our simulation results.

6. Conclusion

In this paper, we have studied the SOP of the AF-based partial relay selection scheme with passive eavesdroppers based on outdated CSI. In addition, we have analyzed the SOP performance over the i.i.d. Rayleigh fading channels. Specifically, the exact SOP analysis has been given in a one-integral form and the asymptotic SOP analysis has been given in a closed-form. Some numerical examples have been given to verify our provided analytical results for different system conditions.

Appendix

Proof of Theorem 1

In (12), we fix the random variable $\gamma_{h_{E_k}}$ as z, $z = \gamma_{h_{E_k}}$, and then the probability of the right hand side can be rewritten as

$$E_z\left[\Pr\left[\frac{\left(1+\tilde{\gamma}_{h_{R_k}}\right)\left(1+\gamma_{h_{D_k}}\right)/\left(\tilde{\gamma}_{h_{R_k}}+\gamma_{h_{D_k}}+1\right)}{\left(1+\tilde{\gamma}_{h_{R_k}}\right)(1+z)/\left(\tilde{\gamma}_{h_{R_k}}+z+1\right)} < T\right]\right]. \tag{A.1}$$

Since z is an exponential random variable with parameter $1/\Omega_3$, (A.1) can be calculated by taking the integral over z of the probability as (13). The probability in (A.1) denoted by $\mathscr{I}(z)$ can be rewritten as

$$\begin{aligned}\mathscr{I}(z) = \Pr\Big[&\left(\tilde{\gamma}_{h_{R_k}} - (T-1)(z+1)\right)\gamma_{h_{D_k}} \\ &< T(z+1)\left(\tilde{\gamma}_{h_{R_k}}+1\right) - \left(\tilde{\gamma}_{h_{R_k}}+z+1\right)\Big].\end{aligned} \tag{A.2}$$

Since $T > 1$ for $C_t > 0$, it is easily shown that the term $T(z+1)(\tilde{\gamma}_{h_{R_k}}+1)-(\tilde{\gamma}_{h_{R_k}}+z+1)$ in (A.2) is always positive. Therefore, the probability $\mathscr{I}(z)$ can be divided into two probabilities as

$$\begin{aligned}\mathscr{I}(z) = \Pr&\left[\tilde{\gamma}_{h_{R_k}} \le (T-1)(z+1)\right] + \Pr\Big[\gamma_{h_{D_k}} \\ &< \mathscr{A}\left(\tilde{\gamma}_{h_{R_k}}, T, z\right), \tilde{\gamma}_{h_{R_k}} > (T-1)(z+1)\Big],\end{aligned} \tag{A.3}$$

where

$$\mathscr{A}\left(\widetilde{\gamma}_{h_{R_k}}, T, z\right) = \frac{T(z+1)\left(\widetilde{\gamma}_{h_{R_k}}+1\right)-\left(\widetilde{\gamma}_{h_{R_k}}+z+1\right)}{\widetilde{\gamma}_{h_{R_k}}-(T-1)(z+1)}. \quad (A.4)$$

Since $\widetilde{\gamma}_{h_{R_k}}$ and $\gamma_{h_{D_k}}$ are independent random variables, the probability $\mathscr{I}(z)$ can be calculated as

$$\begin{aligned}\mathscr{I}(z) &= \int_0^{(T-1)(z+1)} f_{\widetilde{\gamma}_{h_{R_k}}}(x)\,dx \\ &+ \int_{(T-1)(z+1)}^{\infty}\int_0^{\mathscr{A}(x,T,z)} f_{\widetilde{\gamma}_{h_{R_k}}}(x)\, f_{\gamma_{h_{D_k}}}(y)\,dy\,dx \\ &= 1-\int_{(T-1)(z+1)}^{\infty}\overline{F}_{\gamma_{h_{D_k}}}(\mathscr{A}(x,T,z))\, f_{\widetilde{\gamma}_{h_{R_k}}}(x)\,dx.\end{aligned} \quad (A.5)$$

By substituting (8) into (A.5), one can rewrite (A.5) as

$$\begin{aligned}\mathscr{I}(z) &= 1-k\binom{L}{k}\sum_{m=0}^{k-1}\frac{(-1)^m\binom{k-1}{m}}{((L-k+m)(1-\rho)+1)\,\Omega_1} \\ &\times\int_{(T-1)(z+1)}^{\infty}\exp\left(-\frac{\mathscr{A}(x,T,z)}{\Omega_2}\right. \\ &\left.-\frac{\mathscr{B}(k,m)\,x}{\Omega_1}\right)dx,\end{aligned} \quad (A.6)$$

where $\mathscr{B}(k,m) = (L-k+m+1)/((L-k+m)(1-\rho)+1)$. After doing some manipulations with the help of [20, Eq. 3.324.1], the probability $\mathscr{I}(z)$ in (A.6) can be given in (14). Substituting $\mathscr{I}(z)$ in (14) into (A.1) and taking the integral over z of $\mathscr{I}(z)$, finally, we can calculate the exact of SOP of the AF-based partial relay selection $P_{\text{out}}(C_t)$ given in (13).

Conflicts of Interest

The author declares that there are no conflicts of interest.

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