

Secure Communication in Two-Way Relay Networks with Channel Estimation Errors

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Abstract

In this paper, we investigate the secrecy outage probability (SOP) for the cooperative amplify-and-forward (AF) two-way relay networks (TWRN) with channel estimation (CE) errors under Rayleigh fading channels. In the proposed system, two sources simultaneously broadcast their respective information to all the relays firstly. Then, the optimal relay performs AF protocol on the received signals sent from the two sources and forward them to both sources. In both phases, An eavesdropper receives the signals from sources and relay nodes illegally. The performance of the proposed system is quantified by deriving the upper bound of the overall outage probability. Impact of CEs on the system is illustrated by simulations.

Keywords: Two-way relaying network, amplify-and- forward (AF), wiretap channel, channel estimation errors

1. Introduction

Due to their inherent broadcasting nature, wireless communication systems are prone to security threats. One possible way against eavesdropper is utilizing cryptographic encryption, eavesdroppers hardly recover the source information without the secret key. However, the encryption method requires considerable computational resources and communication overheads, which adds another layer of complexity in the design of networks [1]. Another new approach against eavesdropper is physical layer (PHY) security by exploiting the physical characteristics of wireless channels. This work was pioneered by Wyner, who introduced the wiretap channel in 1975 and established the possibility to transmit confidential messages without using secret keys [2]. In order to increase the secrecy rate of networks, cooperative relaying communication is introduced [3], the main objective is to boost the capacity of the primary links by decreasing simultaneously the capacity of the eavesdropper links. Meanwhile, there has been a growing of interest in two-way communications due to its bandwidth efficiency and potential applications to cellular and peer-to-peer networks [4].

One important feature for PHY security is that the channel state information (CSI), including which from the source to the destination as well as from the source to the eavesdropper, should be known by the source and/or the destination to enable signal processing such as beamforming and jamming. Most of the previous research about PHY secure wireless communication have assumed perfect CSI. However, in practical communication systems, CSI is observed by estimation algorithms and CE error is

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inevitable. The reference [5] gives the optimal channel estimation and training design for TWRN and the corresponding problem with the assumption of time-selective channel is considered in [6]. In general, the CE error exists at all communication. Recently, physical layer security in the presence of imperfect CE attracts increasingly attention.

Current developments in PHY security are often based on the assumption of perfect CSI. In [7], authors investigate joint relay and jammer selection in two-way cooperative networks, consisting of two sources, one eavesdropper, and a number of intermediate nodes, with secrecy constraints. Specifically, the proposed schemes select two or three intermediate nodes to enhance security against the malicious eavesdropper. Some works are based on two-way relay networks with imperfect CSI. In [8], authors study the performance of bidirectional multi-relay cooperative networks in the presence of imperfect channel state information by means of the correlation coefficient of the estimated channel gains and their actual values, and present a power allocation scheme that minimizes the outage probability. In [9], authors investigate, the secrecy performance of a single-input single-output single antenna eavesdropper two-way relay wiretap channel, in which only statistical channel state information from the eavesdropper is available at the sources. They propose a secure adaptive transmission scheme for this two-way relay wiretap channel in which the sum effective secrecy throughput is utilized as the performance metric.

A number of analysis in the literature have considered performance in Two-Way Relay Networks With Channel Estimation Errors. In [10], The impact of channel estimation errors is investigated in two-way relay networks (TWRNs) with two different channel state information (CSI) estimation schemes, namely separate and cascaded, and the source nodes in the TWRN are assumed to have different estimation errors. In [11], the outage behavior of decode-and-forward (DF) relaying in the context of selective two-way cooperative systems is investigated. In [12], authors investigate the impact of outdated channel estimates on the overall performance of a two-way multi-relay system that employs a three-phase (3P) analog network coding (ANC)-based opportunistic relay selection (ORS) scheme under Rayleigh fading. In references [13]-[15], effects of imperfect CSI are studied in other wireless communications. In [13], authors analyze the impact of outdated CSI on the security performance in multi-input multi-output (MIMO) system, where the transmitter uses maximal-ratio transmission (MRT) and the receiver uses receive antenna selection (RAS). In their analysis, new closed-form expressions for the probability of the existence of a nonzero secrecy capacity and the secrecy outage probability are derived. In [14], authors analyze the effects of outdated CSI on the secrecy outage performance of MISO wiretap channels with transmit antenna selection. In [15], Yang W. *et. al.*, investigate the secrecy outage probability for the cooperative decode-and-forward underlay cognitive radio networks (CRNs).

In [16], authors investigate jammer selection in a two-way decode-and-forward relay network with imperfect channel state information, under the assumption that the relay can decode received signals perfectly and when the jamming power is higher than that of source nodes. In [17], authors study the channel estimation and data detection problem for secure Amplify-and-Forward two-way relay networks, in which channel estimation errors of both the legal user and the eavesdropper are studied, and they derive the closed-form expression of channel capacity with imperfect channel state information. In [18], joint relay/jammer selection and power control with friendly jammers for physical layer security in two-way relay networks are studied, in which the impact of channel estimation error on the wiretap channel is also considered. To our best knowledge, seldom works study the secrecy outage probability of AF TWRN when channel estimation errors exists.

Motivated by all of the above, we firstly build up a secure amplify-and-forward (AF) TWRN model with channel estimation between the sources and relay nodes. And then, the upper bound of the overall outage probability for the proposed system is investigated. Finally, simulation results indicates that estimation errors decrease the outage

performance of the system both in the same CEs and different CEs for different source-relay channels.

2. System Model

Consider a two-way amplify-and-forward (AF) relaying system, where two sources S_1 and S_2 exchange information with the help of K cooperating AF relay nodes k , $k \in \{1, \dots, K\}$ in the presence of an eavesdropper E , as shown in Figure 1. All channels are assumed quasi-static, reciprocal, and subject to independent and non-identically distributed (i.n.i.d.) flat Rayleigh fading. Furthermore, assume that data transmissions are performed using a time division duplex. As such, the channel coefficients are assumed to remain constant over a block and correlated across blocks, where the block duration depends on the channel coherence time, and every channel gain between the source and k can be modeled as a complex Gaussian random variable, that is, $h_{a,b} \sim \mathcal{CN}(0, \Omega_{ab})$, where $a, b \in \{S_1, S_2, k, E\}$, and $h_{a,b} = h_{b,a}$. We assume that all terminals are single-antenna devices and operate in a half-duplex mode, and there is no direct path between S_1 and S_2 . We also assume here the additive white Gaussian noise (AWGN) at all nodes is independent and identically distributed (i.i.d.) $\mathcal{CN}(0, N_0)$.

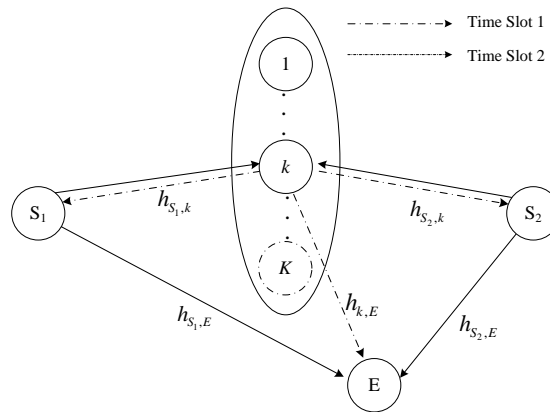


Figure 1. System Model of TWRN with an Eavesdropper

In the first time slot, S_1 and S_2 transmit their signals x_1 and x_2 to all the relays simultaneously. So the received signal at relay k and the received signal at eavesdropping node can be expressed as:

$$y_k = \sqrt{P_{S_1}} h_{S_1,k} x_1 + \sqrt{P_{S_2}} h_{S_2,k} x_2 + n_k, \quad (1)$$

$$y_{e_1} = \sqrt{P_{S_1}} h_{S_1,E} x_1 + \sqrt{P_{S_2}} h_{S_2,E} x_2 + n_{e_1} \quad (2)$$

where P_{S_1} and P_{S_2} are the transmitting power of S_1 and S_2 . $h_{S_1,k}$ and $h_{S_2,k}$ stand for the channel gains of $S_1 \rightarrow k$ and $S_2 \rightarrow k$, respectively. n_k and n_{e_1} are the AWGN at relay node k and the eavesdropper node E in the first time slot, respectively. We model the relation between the channel coefficient $h_{S_i,k}$ and its estimation $\hat{h}_{S_i,k}$ as:

$$h_{S_i,k} = \hat{h}_{S_i,k} + e_{S_i,k}, i = 1, 2, \quad (3)$$

where $e_{S_i,k}$ is distributed as $\mathcal{CN}(0, \sigma_{S_i,k}^2)$, thus, $\hat{h}_{S_i,k}$ is distributed as $\mathcal{CN}(0, \Omega_{S_i,k} - \sigma_{S_i,k}^2)$.

In the second time slot, the received signal at relay k is amplified with the gain $G = \sqrt{P_k / (P_{S_1} |\hat{h}_{S_1,k}|^2 + P_{S_2} |\hat{h}_{S_2,k}|^2 + N_0)}$, and retransmitted to S_1 and S_2 .

Since the sources know their own signal, *i.e.*, S_1 knows x_1 and S_2 knows x_2 , after the self-interference parts are subtracted [1], the received signals at the source S_i and the eavesdropper are expressed as:

$$\begin{aligned}
 y_{S_i} &= Gh_{S_i,k} y_k + n_{S_i} - \sqrt{P_{S_i}} G |\hat{h}_{S_i,k}|^2 x_i \\
 &= \underbrace{G\sqrt{P_{S_j}} \hat{h}_{S_i,k} \hat{h}_{S_j,k} x_j}_{\text{desired signal}} + \underbrace{G\sqrt{P_{S_j}} \hat{h}_{S_i,k} e_{S_j,k} x_j + G\sqrt{P_{S_j}} e_{S_i,k} \hat{h}_{S_j,k} x_j + G\sqrt{P_{S_j}} e_{S_i,k} e_{S_j,k} x_j}_{\text{imperfect-CSI noise(1)}} \\
 &\quad + \underbrace{2G\sqrt{P_{S_i}} \hat{h}_{S_i,k} e_{S_i,k} x_i + G\sqrt{P_{S_i}} e_{S_i,k}^2 x_i}_{\text{imperfect-CSI noise(2)}} + \underbrace{G\hat{h}_{S_i,k} n_k + Ge_{S_i,k} n_k + n_{S_i}}_{\text{white noise}}, i, j \in \{1, 2\}, i \neq j
 \end{aligned} \tag{4}$$

$$\begin{aligned}
 y_{e_2} &= Gh_{k,E} y_k + n_{e_2} \\
 &= G\sqrt{P_{S_i}} h_{k,E} \hat{h}_{S_i,k} x_i + G\sqrt{P_{S_i}} h_{k,E} e_{S_i,k} x_i + G\sqrt{P_{S_j}} h_{k,E} \hat{h}_{S_j,k} x_j \\
 &\quad + G\sqrt{P_{S_j}} h_{k,E} e_{S_j,k} x_j + Gh_{k,E} n_k + n_{e_2}, i, j \in \{1, 2\}, i \neq j
 \end{aligned} \tag{5}$$

The received SNRs of link $S_j \rightarrow k \rightarrow S_i$, $i, j \in \{1, 2\}, i \neq j$ (i, j) is given by

$$\begin{aligned}
 \gamma_i &= \frac{G^2 P_{S_j} \hat{h}_{S_i,k} \hat{h}_{S_j,k}}{(G^2 P_{S_j} |\hat{h}_{S_i,k}|^2 \sigma_{S_j,k}^2 + G^2 P_{S_j} |\hat{h}_{S_j,k}|^2 \sigma_{S_i,k}^2 + G^2 P_{S_j} \sigma_{S_i,k}^2 \sigma_{S_j,k}^2 \\
 &\quad + 4G^2 P_{S_i} |\hat{h}_{S_i,k}|^2 \sigma_{S_i,k}^2 + G^2 P_{S_i} \sigma_{S_i,k}^4 + G^2 |\hat{h}_{S_i,k}|^2 N_0 + G^2 \sigma_{S_i,k}^2 N_0 + N_0)} \\
 &, i, j \in \{1, 2\}, i \neq j
 \end{aligned} \tag{6}$$

Assume the statistic knowledge of the eavesdroppers link could be available from long term eavesdropper supervision in practice, then we can use the expectation $E[|h_{k,E}|^2]$ and $E[|h_{S_i,E}|^2]$ instead of $|h_{k,E}|^2$ and $|h_{S_i,E}|^2$, respectively.

For simplicity, consider the eavesdropper adopts the selection combining (SC) to combine the received signals within two time slots. Thus, the received SNRs of the eavesdropper for x_i , $i, j \in \{1, 2\}, i \neq j$ (i, j) is given by:

$$\gamma_{E_i} = \max \left\{ \frac{P_{S_i} E[|h_{S_i,E}|^2]}{\sigma_{N_{S_i,e_1}}^2}, \frac{G^2 P_{S_i} |\hat{h}_{S_i,k}|^2 E[|h_{k,E}|^2]}{\sigma_{N_{S_i,e_2}}^2} \right\}, \tag{7}$$

where

$$\sigma_{N_{S_i, e_1}}^2 = P_{S_j} |h_{S_j, E}|^2 + N_0, \quad (8)$$

$$\sigma_{N_{S_i, e_2}}^2 = G^2 P_{S_j} |h_{k, E}|^2 \sigma_{S_i, k}^2 + G^2 P_{S_j} |h_{k, E}|^2 |\hat{h}_{S_j, k}|^2 + G^2 P_{S_j} |h_{k, E}|^2 \sigma_{S_j, k}^2 + G^2 |h_{k, E}|^2 N_0 + N_0 \quad (9)$$

The instantaneous capacity of the wiretap channel for x_i and the instantaneous capacity between S_i and the eavesdropper E can be expressed as:

$$C_i = \frac{1}{2} \log_2(1 + \gamma_j), \quad (10)$$

$$C_{E_i} = \frac{1}{2} \log_2(1 + \gamma_{E_i}), \quad (11)$$

respectively. Thus, the secrecy rate for source S_i is

$$R_{S_i} = \left[\frac{1}{2} \log_2(1 + \gamma_j) - \frac{1}{2} \log_2(1 + \gamma_{E_j}) \right]^+, \quad i, j = 1, 2; \quad i \neq j \quad (12)$$

where $[x]^+ \triangleq \max\{0, x\}$.

Since the overall performance of the considered system is governed by the performance of the weakest source. Taking into account the wiretap channel, the optimal relay selection criterion can be expressed as:

$$k^* = \arg \max_{k \in \{1, 2, \dots, K\}} \left\{ \min \left(\frac{1 + \gamma_1}{1 + \gamma_{E_2}}, \frac{1 + \gamma_2}{1 + \gamma_{E_1}} \right) \right\}, \quad (13)$$

3. Performance Analysis

In this section, outage probability of the above-mentioned relay selection schemes under Rayleigh fading channel is analyzed, and expression for the overall outage probability is derived.

With the above selection scheduling, the overall outage probability is given by:

$$\begin{aligned} P_{out} &= \Pr \left\{ \max_{k \in \{1, 2, \dots, K\}} \left\{ \min \left(\frac{1 + \gamma_1}{1 + \gamma_{E_2}}, \frac{1 + \gamma_2}{1 + \gamma_{E_1}} \right) \right\} \leq 2^{2R} - 1 \right\} \\ &= \prod_{k=1}^K \Pr \left\{ \min \left(\frac{1 + \gamma_1}{1 + \gamma_{E_2}}, \frac{1 + \gamma_2}{1 + \gamma_{E_1}} \right) \leq 2^{2R} - 1 \right\} \\ &= \prod_{k=1}^K \left\{ 1 - \Pr \left\{ \min \left(\frac{1 + \gamma_1}{1 + \gamma_{E_2}}, \frac{1 + \gamma_2}{1 + \gamma_{E_1}} \right) \geq 2^{2R} - 1 \right\} \right\} \\ &= \prod_{k=1}^K \left\{ 1 - \Pr \left\{ \frac{1 + \gamma_1}{1 + \gamma_{E_2}} \geq 2^{2R} - 1 \right\} \Pr \left\{ \frac{1 + \gamma_2}{1 + \gamma_{E_1}} \geq 2^{2R} - 1 \right\} \right\} \end{aligned} \quad (14)$$

The two probability expression are parameter symmetrical, so we analysis the first one.

$$\begin{aligned}
 \Pr \left\{ \frac{1 + \gamma_1}{1 + \gamma_{E_2}} \geq \gamma_{th} \right\} &\leq \Pr \left\{ \frac{1 + \gamma_1}{\max \left\{ \frac{P_{S_2} |h_{S_2,E}|^2}{\sigma_{N_{S_2,e_1}}^2}, \frac{G^2 P_{S_2} |\hat{h}_{S_2,k}|^2 |h_{k,E}|^2}{\sigma_{N_{S_2,e_2}}^2} \right\}} \geq \gamma_{th} \right\} \\
 &= \Pr \left\{ \frac{1 + \gamma_1}{\frac{P_{S_2} |h_{S_2,E}|^2}{\sigma_{N_{S_2,e_1}}^2}} \geq \gamma_{th} \right\} \Pr \left\{ \frac{1 + \gamma_1}{\frac{G^2 P_{S_2} |\hat{h}_{S_2,k}|^2 |h_{k,E}|^2}{\sigma_{N_{S_2,e_2}}^2}} \geq \gamma_{th} \right\} \\
 &= P_{out}(1) P_{out}(2)
 \end{aligned} \tag{15}$$

Substituting (6) and (7) into (15), we can simplify $P_{out}(1)$ as:

$$P_{out}(1) = \Pr \left\{ a_1 |\hat{h}_{S_1,k}|^2 |\hat{h}_{S_2,k}|^2 + a_2 a_5 |\hat{h}_{S_1,k}|^2 + a_3 a_5 |\hat{h}_{S_2,k}|^2 + a_4 a_5 \geq 0 \right\}, \tag{16}$$

$$\text{where } a_1 = P_k P_{S_2} \left(P_{S_1} E \left[|h_{S_1,E}|^2 \right] + N_0 \right),$$

$$a_2 = \left(P_k P_{S_2} \sigma_{S_2,k}^2 + 4 P_k P_{S_1} \sigma_{S_1,k}^2 + N_0 P_{S_1} + P_k N_0 \right), \quad a_3 = P_k P_{S_2} \sigma_{S_1,k}^2 + N_0 P_{S_2},$$

$$a_4 = P_k P_{S_2} \sigma_{S_1,k}^2 \sigma_{S_2,k}^2 + P_k P_{S_1} \sigma_{S_1,k}^4 + P_k \sigma_{S_1,k}^2 N_0 + N_0^2, \quad a_5 = P_k P_{S_2} \sigma_{S_1,k}^2 + N_0 P_{S_2},$$

$$a_4 = P_k P_{S_2} \sigma_{S_1,k}^2 \sigma_{S_2,k}^2 + P_k P_{S_1} \sigma_{S_1,k}^4 + P_k \sigma_{S_1,k}^2 N_0 + N_0^2,$$

$$a_5 = P_{S_1} E \left[|h_{S_1,E}|^2 \right] + N_0 - \gamma_{th} P_{S_2} E \left[|h_{S_2,E}|^2 \right].$$

Set $|\hat{h}_{S_1,k}|^2 = x$, $|\hat{h}_{S_2,k}|^2 = y$, $Axy + Bx + Cy + D = z_1$. $|\hat{h}_{S_1,k}|^2$ is an exponential distributed variable with parameter $\lambda_i = 1 / \left[2 \left(\Omega_{S_i,k} - \sigma_{S_i,k}^2 \right) \right]$, $i = 1, 2$. With the help of Eq. 3.324(1) and 3.471(9) in [19], we can obtain:

$$\begin{aligned}
 P_{out}(1) &= \Pr \{ z_1 \geq 0 \} \\
 &= e^{-\frac{\lambda_1 C + \lambda_2 B}{A}} \left[\frac{-2A\sqrt{\lambda_1 \lambda_2 F} K_1 \left(2\sqrt{\lambda_1 \lambda_2 F} \right) - 2AF \cdot K_2 \left(2\sqrt{\lambda_1 \lambda_2 F} \right)}{+\frac{A}{\lambda_2} + 2E\sqrt{\lambda_1 \lambda_2 F} K_1 \left(2\sqrt{\lambda_1 \lambda_2 F} \right) - E} \right]
 \end{aligned} \tag{17}$$

where $E = \frac{BC}{A} - D$, $F = \frac{BC}{A^2} - \frac{D}{A}$. $K_v(z)$ is Bessel function of imaginary argument.

Similarly, After substitution, the form of $P_{out}(2)$ is given by:

$$P_{out}(2) = \Pr(z_2 \geq 0) \\ = \Pr\{A_2x^2y + B_2y^2x + C_2x^2 + D_2y^2 + E_2xy + F_2x + G_2y + H \geq 0\}. \quad (18)$$

The closed-form solve of (18) is hard to obtain. Specially, without regard to interferences between relay nodes, when the eavesdropper acts as an untrusted relay node, $E[|h_{k,E}|^2] = 0$. Thus, $P_{out}(2) = 1$. Then the upper bound of (15) can be derived.

4. Numerical Results

In this section, we present Monte-Carlo simulations to confirm impact of channel estimation errors on the overall outage probability. We assume that the average SNR in links from two sources to relay is equal, *i.e.*, $P_{S1} = P_{S2} = P_k = 1$, number of relay K is 4, The distance between two sources S_1 and S_2 is normalized to 1. Without loss of generality, we set $d_{1k} = 0.5$ for all the relays, and $\Omega_{S_i,k} = 1$, $E[|h_{k,E}|^2] = E[|h_{S_i,E}|^2] = 2$. The targeted transmission rate $R = 1$ bit/s/Hz.

Figure 2 shows the actual simulation results for the overall outage probability when $K = 4$. The curve with $\sigma_{S_1,k}^2 = \sigma_{S_2,k}^2 = 0$ represents the case of perfect channel estimation in the proposed system. As expected, we can see that either of the channel estimation errors $\sigma_{S_1,k}^2$ and $\sigma_{S_2,k}^2$ affects the overall outage probability, that is, as the CEs increase, whether they are different or not, the system outage performance degrades.

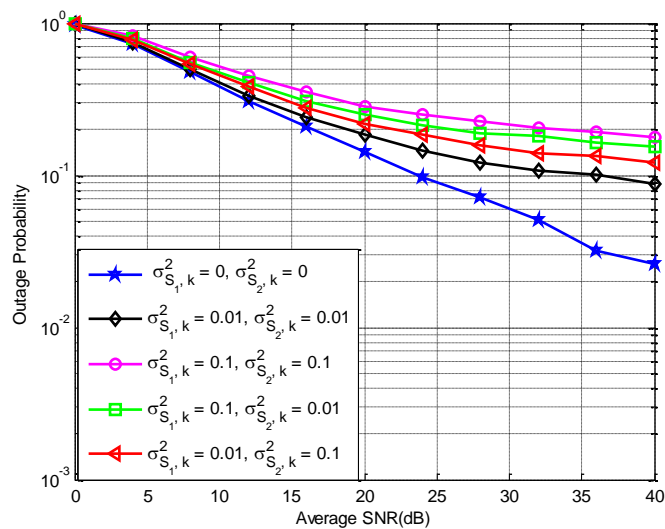


Figure 2. Outage Probability Against SNR for $K = 4$

5. Conclusion

In this paper, we analysis the impact of the imperfect CSI (or CEs) in amplify-and-forward two-way relay networks with an eavesdropper over independent flat Rayleigh fading channels. To research the performance of two way networks under security threat, relay selection is performed in accordance with the max-min rule and the expression of SOP is studied, and then Numerical results show that performance of the system degrades as either of the two CEs increases, no matter whether CEs are different or not.

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