IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received July 18, 2019, accepted July 24, 2019, date of publication July 30, 2019, date of current version August 15, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2932135

Secrecy Outage Probability Analysis for Full-Duplex Relaying Networks Based on Relay Selection Schemes

QINGFENG DING, MENGXIA LIU, AND YUQIAN DENG
College of Electrical and Automation Engineering, East China Jiaotong University, Nanchang 330013, China

Corresponding author: Mengxia Liu (2534847230@qq.com)

This work was supported in part by the National Natural Science Foundation of China under Grant 61501186, in part by the Jiangxi Province Science Foundation of China under Grant 20171BAB202001 and Grant 20192ACB21003, in part by the Jiangxi Province Foundation for Distinguished Young Scholar under Grant 20192BCB23013, and in part by the Jiangxi Province Department of Education Science and Technology Research Project of China under Grant GJJ180307.

ABSTRACT Considering existing eavesdroppers, this paper analyzes the secrecy outage probability (SOP) of the full-duplex (FD) relaying network with imperfect channel state information (CSI), where the decode-and-forward relay protocol is adopted. To enhance the physical-layer security, two relay selection schemes are proposed. The first scheme uses the maximum–minimum principle to select the optimal relay. The other selection scheme is based on partial signal-to-interference-plus-noise ratio. Then, the tight closed-form approximations of the SOP are obtained for three special CSI cases, respectively. Moreover, based on these approximated results, the effects of some system parameters are analyzed for the SOP of the relay system, including the CSI error, the number of relays, the signal-to-noise ratio (SNR) of the eavesdropper, and the residual self-interference caused by the FD model. The numerical results show that at low SNR of the eavesdropper, residual self-interference has a significantly impact on SOP, while at high SNR of the eavesdropper, this effect is negligible. In addition, the SOP of FD model is always superior to the half-duplex (HD) model when the number of relays changes.

INDEX TERMS Relay selection, full-duplex, imperfect CSI, decode-and-forward, secrecy outage probability.

I. INTRODUCTION

Due to the broadcasting characteristics of wireless communication, physical layer security technology has received extensive attention from researchers [1]. Wyner defined the secrecy rate, which was the maximum rate at which reliable information was sented from the source to the destination in the presence of an eavesdropper [2]. Then, the physical layer security technology was applied to various network scenarios, e.g., wireless cooperative networks.

Wireless cooperative communication can increase the capacity of the system, and physical layer security aims to increase the system's secure capacity. Therefore, the combination of physical layer security technology and wireless cooperative communication can improve the security of the system. In [3] the authors studied the security of Fountain codes in low-energy adaptive clustering hierarchy networks. In cooperative communication, we can ensure secure communication through beamforming [4], artificial noise [5], [6], relay selection [7] and other means. A secure beamforming design for the cognitive radio Networks in the presence of multiple eavesdroppers was studied [4]. A new design paradigm was studied in secure full-duplex (FD) multiuser system to maximize the minimum secrecy rate among all legitimate users [5]. An artificial noise aided scheme was studied in massive multiple-input multiple-output (MIMO) non-orthogonal multiple access (NOMA) networks to ensure secrecy [6]. Three relay selection schemes to choose the best relay for underlay cooperative cognitive network with the presence of multiple eavesdroppers [7]. The relay selection technology was one of key technologies in of Wireless cooperative communication [8]. Considering the physical layer

The associate editor coordinating the review of this manuscript and approving it for publication was Aniello Castiglione.

security of multiple relay cooperative networks, the impact of the relay selection scheme on the security of the cooperative network need to be studied.

At present, the physical layer security technology has been perfectly applied to the relay network, and widely studied by scholars and engineers all over the world [9]–[12]. In [9], the optimal and suboptimal relay selection schemes were proposed, and the secrecy outage probability (SOP) was derived. In addition, the concept of physical layer security in wireless relay networks had been further summarized in [10], and full-duplex (FD) relay was considered to be an important research direction in the future. For the optimal relay selection of secure FD relay system, by analyzing the performance of SOP, the FD-based relay selection scheme was compared with the traditional half-duplex (HD) relay selection scheme in [11]. Considering the untrusted relays and passive eavesdroppers, a joint relay selection and power allocation scheme for massive multiple-input multiple-output (MIMO) system was proposed in [12] to enhance physical layer security.

All the aforementioned references suppose that the channel state information (CSI) for each channel is perfect. However, in practice, the CSI is imperfect, e.g., [13]–[16]. The work in [13] studied the imperfect CSI for a multipair massive MIMO two-way amplify-and-forward (AF) relay network and the approximation expression of the spectral efficiency (SE) was derived. In [14], the expressions of SE and energy efficiency (EE) for the multi-pair two-way AF relay system with imperfect CSI over Ricean fading channels were derived. The work in [15] studied the eavesdrop channel for the AF two-way relay system, and the expression of relay transmission power was derived. In [16], the approximate expression of the outage probability was derived for a multi-user massive MIMO system with mixed-precision analog-to-digital converter (ADC) and imperfect CSI.

In the secure relay system, the secrecy rate and the SOP are important performance criterions in evaluating system security. Many scholars analyze the security performance of the systems by analyzing the expressions for SOP. The work in [17] studied the multiple-relay assisted non-orthogonal multiple access network and the optimal single, two step single and optimal dual relay selection schemes were proposed. The expressions of SOP for the three relay selection scheme were derived. The secrecy performance of modify-and-forward multi-relay and multi-eavesdropper networks was investigated and the closed-form expressions for the SOP were obtained in [18]. The secrecy performance of a two-hop cooperative cognitive relay network was investigated in [19] and the SOP was derived. The radio frequency energy harvesting and relay selection of the wireless sensor network in the presence of multiple eavesdroppers were analyzed and exact closed-form expressions for SOP were derived in [20].

In this paper, a FD relay system with multiple relays and an eavesdropper is considered. The channels between the relays and the users are assumed to be imperfect CSI. The main contributions of our work are summarized as follows.

- Differently from the results in the previously published work [21], [22], we study the FD relaying networks with two relay selection schemes. In contrast to [23], we focus on the FD and HD relaying networks and consider imperfect CSI, respectively.
- In order to enhance the physical layer security, the appropriate relay is selected by two relay selection schemes. The first scheme is proposed for the secure relay network with imperfect CSI, which selects the optimal relay according to maximizing the end-to-end security capacity.
- The second scheme is proposed for the secure FD relay network with imperfect CSI, which selects the relay according to maximizing the partial signal-to-interference-plus-noise ratio.
- The closed-form expressions of SOP for two relay selection schemes are derived for the FD relay network, respectively. By considering three cases of imperfect CSI, the SOPs are further derived, based on which useful insights of the SOP behavior with respect to different system parameters are obtained.
- The HD relay network SOP performance with the first relay selection scheme is further analyzed, and the approximate expressions based on three imperfect CSI cases are obtained. For imperfect CSI, we also verify these conclusions through numerical results.

Notations: $\overline{\gamma}_{a,b}$, $\hat{\gamma}_{a,b}$ and $\Delta\gamma_{a,b}$ stand for the mean, estimated and estimated error SNR of $a \rightarrow b$ link, respectively. $f_X(\cdot)$ and $F_X(\cdot)$ represent the probability density function (PDF) and the cumulative distribution function (CDF) of random variable X, respectively.

II. SYSTEM MODEL

We consider a cooperative relaying system, which consists of two legitimate users (i.e. S_1 and S_2), an eavesdropper (i.e. E) and N relays as denoted by the set of $\Omega = \{R_k, k = 1, 2, \cdots, N\}$. And there is no direct link between S_1 and S_2. It is assumed that all terminals are equipped with a single antenna, except that the relays are equipped with two antennas. Meanwhile, the decode-and-forward (DF) protocol is applied. Since the FD mode is employed in the relay node, there is residual self-interference (SI) in the relay nodes, where residual SI is not eliminated by the SI cancellation technique.

Since the research in this paper focuses on the comparison and discussion about the channel CSI of legitimate users, the CSI of the eavesdropping channel is assumed to be perfect.[1] For relay systems with CSI error, we consider the SNR of $a \rightarrow b$ link: $\gamma_{a,b} = \hat{\gamma}_{a,b} + \Delta\gamma_{a,b}$, where $\hat{\gamma}_{a,b}$ is the estimated SNR of $a \rightarrow b$ link, $\Delta\gamma_{a,b}$ is the estimated error

---

[1] The CSI for the eavesdropper is unknown, but assumes that channel statistic information for the eavesdropper is available regarded. This assumption is determined to be feasible in [24].

SNR of $a \to b$ link.[2] $\hat{\gamma}_{a,b}$ and $\Delta\gamma_{a,b}$ are assumed to be independent.

Since all channel follow independent identically distributed (i.i.d) flat Rayleigh fading, $\hat{\gamma}_{a,b}$, $\Delta\gamma_{a,b}$ and $\gamma_{a,b}$ are exponentially distributed random variables with the PDF of the SNR $f_{\hat{\gamma}_{a,b}}(x) = 1/((1-\delta_e^2)\overline{\gamma}_{a,b}) \cdot \exp(-x/((1-\delta_e^2)\overline{\gamma}_{a,b}))$ (δ_e^2 represents the power of the CSI error), $f_{\Delta\gamma_{a,b}}(x) = 1/(\delta_e^2\overline{\gamma}_{a,b}) \cdot \exp(-x/(\delta_e^2\overline{\gamma}_{a,b}))$ and $f_{\gamma_{a,b}}(x) = 1/\overline{\gamma}_{a,b} \cdot \exp(-x/\overline{\gamma}_{a,b})$, respectively. In addition, the noise of link is subjected to zero-mean additive white Gaussian noise (AWGN). Similarly to the noise, the instantaneous power of residual SI (i.e., $\overline{\gamma}_{R_k,R_k}$) is considered to be a certain parameter. Therefore, the signal-to-interference-plus-noise ratio (SINR) at R_k can be represented as

$$\Phi_{R_{k1}} = \frac{\hat{\gamma}_{S_1,R_k}}{\overline{\gamma}_{R_k,R_k} + \Delta\gamma_{S_1,R_k} + 1}. \tag{1}$$

Similarly, the received instantaneous SNR at S_2 can be given by

$$\Phi_{S_2} = \frac{\hat{\gamma}_{R_k,S_2}}{\Delta\gamma_{R_k,S_2} + 1}. \tag{2}$$

In this paper, the eavesdropper ignores the interference noise. Meanwhile, the eavesdropping channels is assumed to weak, and the SOP is given out an upper bound. Therefore, the instantaneous SNR at E from $S_1 \to E$ and $R_k \to E$ can be denoted by $\Phi_{E_1} = \gamma_{S_1,E}$ and $\Phi_{E_2} = \gamma_{R_k,E}$, respectively.

III. RELAY SELECTION SCHEME

In this section, two relay selection schemes are studied. In order to enhance the physical layer security of the relay network, the relay is selected from the N candidate relays to participate in the cooperative communication. One is based on maximum end-to-end security capacity, and other scheme is based on partial signal-to-interference-plus-noise ratio.

A. RELAY SELECTION SCHEME BASED ON MAXIMUM END-TO-END SECURITY CAPACITY

In this subsection, we propose the relay selection scheme based on maximum end-to-end security capacity. Differently from [26], the optimal relay of this scheme is selected by the maximum-minimum principle. Specifically, first the minimum security capacity between the $S_1 \to R_k$ link and the $R_k \to S_2$ link is selected and then the maximum end-to-end security capacity is selected.

The scheme is presented as Algorithm 1. Firstly, the variable R_k represents the kth relay, and the number of relays is initialized, that is, there are N candidate relays. After initialization, the SINR at R_k and the SNR at S_2 can be calculated in step 3 and step 4. Meanwhile, the SNR at E from $S_1 \to E$ and $R_k \to E$ can be calculated in step 5. Then, the security capacity between the $S_1 \to R_k$ link and the $R_k \to S_2$ link can be calculated in step 6 and step 7. And the end-to-end security capacity can be calculated in step 8. Based on the Algorithm 1, the system security capacity can be calculated based on maximum the end-to-end security capacity and the optimal relay is selected based on maximum the end-to-end security capacity.

Algorithm 1 Relay Selection Scheme Based on Maximum End-to-End Security Capacity

```
Input: $\hat{\gamma}_{S_1,R_k}, \hat{\gamma}_{R_k,S_2}, \Delta\gamma_{S_1,R_k}, \Delta\gamma_{R_k,S_2}, \gamma_{S_1,E}, \gamma_{R_k,E}, N$
Output: $C_S, k^*$
1  Initialize $\Omega = \{R_k, k = 1, 2, \cdots, N\}$
2  for $k = 1 : N$ do
3      $\Phi_{R_{k1}} = \frac{\hat{\gamma}_{S_1,R_k}}{\overline{\gamma}_{R_k,R_k} + \Delta\gamma_{S_1,R_k} + 1}$
4      $\Phi_{S_2} = \frac{\hat{\gamma}_{R_k,S_2}}{\Delta\gamma_{R_k,S_2} + 1}$
5      $\Phi_{E_1} = \gamma_{S_1,E}, \Phi_{E_2} = \gamma_{R_k,E}$
6      $\vartheta_1 = \frac{1+\Phi_{R_{k1}}}{1+\Phi_{E_1}}, \vartheta_2 = \frac{1+\Phi_{S_2}}{1+\Phi_{E_2}}$
7      $C_{S_1} = \log_2(\vartheta_1), C_{S_2} = \log_2(\vartheta_2)$
8      $C_{S_k} = \min\{C_{S_1}, C_{S_2}\}$
9  end
10 $C_S = \max_{R_k \in \Omega}\{C_{S_k}\}, k^* = \arg\max_{R_k \in \Omega}\{C_{S_k}\}$
```

B. RELAY SELECTION SCHEME BASED ON MAXIMUM PARTIAL SIGNAL-TO-INTERFERENCE-PLUS-NOISE RATIO

In this subsection, we propose the relay selection scheme based on partial signal-to-interference-plus-noise ratio. Differently from [27], this paper considers the relay selection scheme for the relay system with an eavesdropper. This relay selection scheme selects the relay based on maximum the SINR at R_k. The scheme is presented as Algorithm 2.

Algorithm 2 Relay Selection Scheme Based on Maximum Partial Signal-to-Interference-Plus-Noise Ratio

```
Input: $\hat{\gamma}_{S_1,R_k}, \hat{\gamma}_{R_k,S_2}, \Delta\gamma_{S_1,R_k}, \Delta\gamma_{R_k,S_2}, \gamma_{S_1,E}, \gamma_{R_k,E}, N$
Output: $C_S, k^*$
1  Initialize $\Omega = \{R_k, k = 1, 2, \cdots, N\}$
2  for $k = 1 : N$ do
3      $\Phi_{R_{k1}} = \frac{\hat{\gamma}_{S_1,R_k}}{\overline{\gamma}_{R_k,R_k} + \Delta\gamma_{S_1,R_k} + 1}$
4  end
5  $\Phi_{S_2} = \frac{\hat{\gamma}_{R_k,S_2}}{\Delta\gamma_{R_k,S_2} + 1}$
6  $\Phi_{E_1} = \gamma_{S_1,E}, \Phi_{E_2} = \gamma_{R_k,E}$
7  $\vartheta_1 = \frac{1+\max_{R_k \in \Omega}\{\Phi_{R_{k1}}\}}{1+\Phi_{E_1}}, \vartheta_2 = \frac{1+\Phi_{S_2}}{1+\Phi_{E_2}}$
8  $C_{S_1} = \log_2(\vartheta_1), C_{S_2} = \log_2(\vartheta_2)$
9  $C_S = \min\{C_{S_1}, C_{S_2}\}, k^* = \arg\max_{R_k \in \Omega}\{\Phi_{R_{k1}}\}$
```

Firstly, the variable R_k represents the kth relay, and the number of relays is initialized, that is, there are

---

[2] Please note the outdated CSI caused by the time variation of the channel is not negligible in the actual system, which makes the selected relay not the best data transmission [25].

N candidate relays. After initialization, the SINR at R_k can be calculated in step 3. After that, the SNR at S_2 can be calculated in step 5, at the same time the SNR at E from $S_1 \rightarrow E$ and $R_k \rightarrow E$ can be calculated in step 6. Then, the security capacity between the $S_1 \rightarrow R_k$ link and the $R_k \rightarrow S_2$ link can be calculated in step 7 and step 8. Based on the Algorithm 2, the system security capacity can be calculated based on minimum the security capacity between the $S_1 \rightarrow R_k$ link and the $R_k \rightarrow S_2$ link and the relay is selected based on maximum the SINR at R_k.

C. THE COMPLEXITY OF TWO RELAY SELECTION SCHEMES

In this subsection, the complexity of two relay selection schemes is analyzed. From the above results, Algorithm 1 selects the optimal relay according to the end-to-end security capacity of the relay system, and Algorithm 2 selects a relay according to the partial SINR of the relay system, which is the SINR at the relay. Meanwhile, both algorithms select a relay from N candidate relays. So both algorithms have only one for loop, but the divide statements in the for loop are different. Algorithm 1 has 4 division statements in the for loop, which are calculated in each iteration. Algorithm 2 is only one division statement in the for loop. Thus, the complexity of the algorithm 2 is lower than that of the algorithm 1.

IV. SECRECY OUTAGE PROBABILITY FOR RELAY NETWORK

In this section, these exact and approximation closed-form expressions of the SOP are derived in FD relay network with two relay selection schemes, respectively. And the HD relay network scenario is discussed.

A. FD RELAY NETWORK WITH MAXIMUM END-TO-END SECURITY CAPACITY SCHEME

In this subsection, the FD relay network is studied by using the relay selection scheme based on maximum end-to-end security capacity (Algorithm 1), and the channels between the users and relays are assumed with imperfect CSI. Based on the above relay selection schemes, these exact and approximation closed-form expressions of the SOP are derived. According to the definition of the outage probability, the closed-form expression of the SOP for the system with imperfect CSI can be derived as

$$P_{\mathrm{SOP}} = \Pr\{C_S < r\} = F(\alpha), \tag{3}$$

where r represents the target transmission rate, and $\alpha = 2^r$ indicates the threshold of the FD relay system.

Here, three special cases are considered, i.e., large CSI error, small CSI error and perfect CSI. Based on Algorithm 1, the following lemma presents the exact expression for the SOP of FD relay network with large CSI error.

Lemma 1: When the CSI error between the user and the relay is large, the SOP of the FD relaying system with relay selection can be derived as (4), as shown at the bottom of this page.

Proof: For the secure FD multi-relay systems, the formula (3) can be further derived as

$$\begin{aligned} F(\alpha) &= [1-(1-F_{\vartheta_1}(\alpha))(1-F_{\vartheta_2}(\alpha))]^N \\ &= \int_0^{\infty} f_{\Phi_{E_1}}(y)[1-(1-F_{\vartheta_1|\Phi_{E_1}}(\alpha))(1-F_{\vartheta_2}(\alpha))]^N dy. \end{aligned} \tag{6}$$

According to the above formula (1), the CDF of $\Phi_{R_{k1}}$ can be derived as

$$F_{\Phi_{R_{k1}}}(\alpha) = 1 - \frac{1-\delta_e^2}{\alpha\delta_e^2 + 1 - \delta_e^2} \cdot \exp\left(-\frac{\alpha(\overline{\gamma}_{R_k,R_k}+1)}{(1-\delta_e^2)\overline{\gamma}_{S_1,R_k}}\right). \tag{7}$$

The CDF of ϑ_1 conditioned on Φ_{E_1} can be derived as

$$\begin{aligned} F_{\vartheta_1|\Phi_{E_1}}(\alpha) &= 1 - \exp\left(-\frac{(\alpha(1+\Phi_{E_1})-1)(\overline{\gamma}_{R_k,R_k}+1)}{(1-\delta_e^2)\overline{\gamma}_{S_1,R_k}}\right) \\ &\quad \times \frac{1-\delta_e^2}{(\alpha(1+\Phi_{E_1})-1)\delta_e^2 + 1 - \delta_e^2}. \end{aligned} \tag{8}$$

Meanwhile, according to the above formula (2), the CDF of Φ_{S_2} can be derived as

$$F_{\Phi_{S_2}}(\alpha) = 1 - \frac{1-\delta_e^2}{\alpha\delta_e^2 + 1 - \delta_e^2} \cdot \exp\left(-\frac{\alpha}{(1-\delta_e^2)\overline{\gamma}_{R_k,S_2}}\right). \tag{9}$$

$$\begin{aligned} F(\alpha) &= \sum_{n=0}^{N} \binom{N}{n} \frac{1}{\overline{\gamma}_{S_1,E}} \cdot \left(\frac{1-\delta_e^2}{\alpha\delta_e^2\overline{\gamma}_{R_k,E}} \cdot \frac{1-\delta_e^2}{\alpha\delta_e^2}\right)^n \cdot \upsilon_1^n(\alpha) \cdot \varsigma_1^{n-1}(n\alpha) \cdot \exp\left(n\beta(\alpha)\cdot\mu(\alpha)\right) \\ &\quad \times (\mathrm{Ei}(-\beta(\alpha)\cdot\mu(\alpha)))^n \cdot \exp\left(\varsigma_1(n\alpha)\cdot\beta(\alpha)\right) \cdot \Gamma(-n+1, \varsigma_1(n\alpha)\cdot\beta(\alpha)), \end{aligned} \tag{4}$$

where

$$\begin{aligned} \upsilon_1(\alpha) &= \exp\left(-(\alpha-1)\cdot\left(\frac{1}{(1-\delta_e^2)\overline{\gamma}_{R_k,S_2}} + \frac{\overline{\gamma}_{R_k,R_k}+1}{(1-\delta_e^2)\overline{\gamma}_{S_1,R_k}}\right)\right), \quad \beta(\alpha) = \frac{\alpha-1}{\alpha} + \frac{1-\delta_e^2}{\alpha\delta_e^2}, \\ \mu(\alpha) &= \frac{\alpha}{(1-\delta_e^2)\overline{\gamma}_{R_k,S_2}} + \frac{1}{\overline{\gamma}_{R_k,E}}, \varsigma_1(n\alpha) = \frac{n\alpha(\overline{\gamma}_{R_k,R_k}+1)}{(1-\delta_e^2)\overline{\gamma}_{S_1,R_k}} + \frac{1}{\overline{\gamma}_{S_1,E}} \end{aligned} \tag{5}$$

The CDF of ϑ_2 can be derived as

$$F_{\vartheta_2}(\alpha) = 1 - \frac{1-\delta_e^2}{\alpha\delta_e^2\overline{\gamma}_{R_k,E}} \cdot \exp\left(-\frac{\alpha-1}{(1-\delta_e^2)\overline{\gamma}_{R_k,S_2}}\right) \times (-\exp(\beta(\alpha)\mu(\alpha)) \cdot \mathrm{Ei}(-\mu(\alpha)\beta(\alpha))), \quad (10)$$

where $\mathrm{Ei}(x) = \int_{-\infty}^{x} e^t t^{-1} dt$. With the help of [28, eq.(3.352.4)], formula (10) can be easily derived.

Therefore, from (6), (8) and (10), the exact expression of the SOP can be given by

$$F(\alpha) = \sum_{n=0}^{N} \binom{N}{n} \frac{1}{\overline{\gamma}_{S_1,E}} \left(\frac{1-\delta_e^2}{\alpha\delta_e^2\overline{\gamma}_{R_k,E}}\right)^n \times \exp\left(-\frac{n(\alpha-1)}{(1-\delta_e^2)\overline{\gamma}_{R_k,S_2}}\right) \cdot \varrho(\alpha) \times \exp(n\beta(\alpha)\mu(\alpha)) \cdot (\mathrm{Ei}(-\mu(\alpha)\beta(\alpha)))^n, \quad (11)$$

where

$$\varrho(\alpha) = \varsigma_1^{n-1}(n\alpha)\Gamma(-n+1, \varsigma_1(n\alpha)\beta(\alpha)) \cdot \left(\frac{1-\delta_e^2}{\alpha\delta_e^2}\right)^n \times \exp\left(-\frac{n(\alpha-1)(\overline{\gamma}_{R_k,R_k}+1)}{(1-\delta_e^2)\overline{\gamma}_{S_1,R_k}} + \varsigma_1(n\alpha)\beta(\alpha)\right). \quad (12)$$

with $\Gamma(x, y) = \int_{y}^{\infty} e^{-t} t^{x-1} dt$. With the help of [28, eq.(3.462.15)], formula (12) can be easily derived. ■

As can be seen from the exact expression of the SOP, the relevant parameters affecting the secure performance of the system are the CSI error, the number of relays, the SNR of the eavesdropper, and the residual SI caused by the FD model. However, the impact of the relevant parameters in special cases on the SOP is not known. Thus, the HD relay scheme is compared with the FD relay scheme.

The difference between the HD relay scheme and FD relay scheme is no self-interference at the HD relay. By analyzing the HD relay scheme, the influence parameters of the exact expression for the SOP without SI are analyzed. The SOP for the HD relay scheme is given by

$$F(\alpha_1) = \sum_{n=0}^{N} \binom{N}{n} \frac{1}{\overline{\gamma}_{S_1,E}} \cdot \left(\frac{1-\delta_e^2}{\alpha_1\delta_e^2\overline{\gamma}_{R_k,E}} \cdot \frac{1-\delta_e^2}{\alpha_1\delta_e^2}\right)^n \times \upsilon_2^n(\alpha_1) \cdot \varsigma_2^{n-1}(n\alpha_1) \cdot \exp(n\beta(\alpha_1) \cdot \mu(\alpha_1)) \times (\mathrm{Ei}(-\beta(\alpha_1) \cdot \mu(\alpha_1)))^n \cdot \exp(\varsigma_2(n\alpha_1) \cdot \beta(\alpha_1)) \times \Gamma(-n+1, \varsigma_2(n\alpha_1) \cdot \beta(\alpha_1)), \quad (13)$$

where

$$\upsilon_2(\alpha_1) = \exp\left(-\frac{\alpha_1-1}{(1-\delta_e^2)\overline{\gamma}_{R_k,S_2}} - \frac{\alpha_1-1}{(1-\delta_e^2)\overline{\gamma}_{S_1,R_k}}\right), \quad (14)$$

$$\varsigma_2(n\alpha_1) = \frac{n\alpha_1}{((1-\delta_e^2)\overline{\gamma}_{S_1,R_k})} + \frac{1}{\overline{\gamma}_{S_1,E}}, \quad (15)$$

with $\alpha_1 = 2^{2r}$ indicates the threshold of the HD relay system.

Based on Algorithm 1, the following lemma presents the exact expression for the SOP of FD relay network with small CSI error.

Lemma 2: When the CSI error between the users and relays is small, the SOP of the FD relaying system with relay selection can be approximated as (16), as shown at the bottom of this page.

Proof: When imperfect CSI estimation error $\delta_e^2 \to 0$, the $\mu(\alpha)\beta(\alpha) \to \infty$ and $\varsigma_1(n\alpha)\beta(\alpha) \to \infty$. Therefore, the limits of $f(\delta_e^2)$ (where $f(\delta_e^2) = \exp(\beta(\alpha)\mu(\alpha)) \cdot \mathrm{Ei}(-\beta(\alpha)\mu(\alpha))$) and $g(\delta_e^2)$ (where $g(\delta_e^2) = \exp(\varsigma_1(n\alpha)\beta(\alpha)) \cdot \Gamma(-n+1, \varsigma_1(n\alpha)\beta(\alpha))$) can be approximated as

$$\lim_{\delta_e^2 \to 0} f(\delta_e^2) \approx -\frac{1}{\beta(\alpha)\mu(\alpha)}. \quad (17)$$

$$\lim_{\delta_e^2 \to 0} g(\delta_e^2) \approx (\varsigma_1(n\alpha)\beta(\alpha))^{-n}. \quad (18)$$

■

Similarly, the results of Lemma 2 indicate that the relevant parameters affecting the secure performance of the system are the CSI error, the number of relays, the SNR of the eavesdropper, and the residual SI caused by the FD model. And the SOP with small CSI error for the HD relay scheme can be approximated as

$$F(\alpha_1) \approx \sum_{n=0}^{N} \binom{N}{n} \frac{(-1)^n}{\overline{\gamma}_{S_1,E}} \cdot \left(\frac{1-\delta_e^2}{\alpha_1\delta_e^2\overline{\gamma}_{R_k,E}} \cdot \frac{1-\delta_e^2}{\alpha_1\delta_e^2}\right)^n \times \upsilon_2^n(\alpha_1) \cdot \frac{1}{\varsigma_2(n\alpha_1)} \cdot \left(\frac{1}{\beta(\alpha_1)}\right)^{2n} \cdot \left(\frac{1}{\mu(\alpha_1)}\right)^n. \quad (19)$$

Based on Algorithm 1, the following lemma presents the exact expression for the SOP of FD relay network with perfect CSI.

Lemma 3: Basically, perfect CSI can be regarded as a special case of imperfect CSI with $\delta_e^2 = 0$, and the SOP of the FD relaying system with relay selection can be derived as (20), as shown at the bottom of this page.

$$F(\alpha) \approx \sum_{n=0}^{N} \binom{N}{n} \frac{(-1)^n}{\overline{\gamma}_{S_1,E}} \cdot \left(\frac{1-\delta_e^2}{\alpha\delta_e^2\overline{\gamma}_{R_k,E}} \cdot \frac{1-\delta_e^2}{\alpha\delta_e^2}\right)^n \cdot \upsilon_1^n(\alpha) \cdot \frac{1}{\varsigma_1(n\alpha)} \cdot \left(\frac{1}{\beta(\alpha)}\right)^{2n} \cdot \left(\frac{1}{\mu(\alpha)}\right)^n \quad (16)$$

$$F(\alpha) = \sum_{n=0}^{N} \binom{N}{n} (-1)^n \cdot \left(\frac{\overline{\gamma}_{R_k,S_2}}{\alpha\overline{\gamma}_{R_k,E} + \overline{\gamma}_{R_k,S_2}}\right)^n \cdot \exp\left(-\frac{n(\alpha-1)}{\overline{\gamma}_{R_k,S_2}}\right) \times \frac{\overline{\gamma}_{S_1,R_k}}{n\alpha\overline{\gamma}_{S_1,E}(\overline{\gamma}_{R_k,R_k}+1) + \overline{\gamma}_{S_1,R_k}} \cdot \exp\left(-\frac{n(\alpha-1)(\overline{\gamma}_{R_k,R_k}+1)}{\overline{\gamma}_{S_1,R_k}}\right) \quad (20)$$

The results in (20) embraces the ones in [11] as special cases. The difference is system model, thus, the parameters affecting the secure performance of the system are different. Similarly, the results of Lemma 3 indicate that the relevant parameters affecting the secure performance of the system are the CSI error, the number of relays, the SNR of the eavesdropper, and the residual SI caused by the FD model. And the SOP with perfect CSI for the HD relay scheme is given by

$$F(\alpha_1) = \sum_{n=0}^{N} \binom{N}{n} \left(\frac{-\overline{\gamma}_{R_k,S_2}}{\alpha_1 \overline{\gamma}_{R_k,E} + \overline{\gamma}_{R_k,S_2}} \right)^n \frac{\overline{\gamma}_{S_1,R_k}}{n\alpha_1 \overline{\gamma}_{S_1,E} + \overline{\gamma}_{S_1,R_k}} \times \exp\left(\frac{n(1-\alpha_1)}{\overline{\gamma}_{S_1,R_k}} + \frac{n(1-\alpha_1)}{\overline{\gamma}_{R_k,S_2}} \right). \quad (21)$$

B. FD RELAY NETWORK WITH MAXIMUM PARTIAL SIGNAL-TO-INTERFERENCE-PLUS-NOISE RATIO SCHEME

In this subsection, the FD relay network is adopted the relay selection scheme based on maximum partial SINR (Algorithm 2), and the channels between the users and relays are assumed with imperfect CSI. According to the definition of the outage probability and the above relay selection scheme, the closed-form expression of the SOP for the system with imperfect CSI can be derived as

$$F(\alpha) = 1 - (1 - F_{\vartheta_1}(\alpha))(1 - F_{\vartheta_2}(\alpha)), \quad (22)$$

where

$$F_{\vartheta_1}(\alpha) = \int_0^{\infty} f_{\Phi_{E_1}}(y)[F_{\Phi_{R_{k1}}}(\alpha(y+1)-1)]^N dy, \quad (23)$$

$$F_{\vartheta_2}(\alpha) = \int_0^{\infty} f_{\Phi_{E_2}}(y) F_{\Phi_{S_2}}(\alpha(y+1)-1) dy. \quad (24)$$

Here, three special cases are considered, i.e., large CSI error, small CSI error and perfect CSI. Based on Algorithm 2, the following Lemma 4 presents the exact expression for the SOP of FD relay network with large CSI error, small CSI error and perfect CSI, respectively.

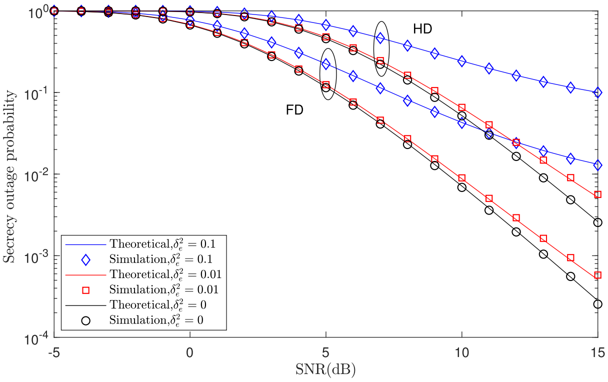


FIGURE 1. The SOP versus the average SNR for different CSI error.

Lemma 4: When the CSI errors between the user and the relay are large, small and zero, the SOPs of the FD relaying system with relay selection can be derived as (25) and (26), as shown at the bottom of this page, and (27), as shown at the bottom of this page, respectively.

V. NUMERICAL RESULTS

In this section, we present analysis and simulation results for SOP with different relay selection schemes and three CSI cases. And the four vital parameters about SOP performance are discussed. In each simulation, the average SNR of the link between the users and relays is considered the same, i.e. $\overline{\gamma}_{S_1,R_k} = \overline{\gamma}_{R_k,S_2} = \overline{\gamma} = 10$dB. Similarity, $\overline{\gamma}_{S_1,E} = \overline{\gamma}_{R_k,E} = \overline{\gamma}_E = -10$dB and $\overline{\gamma}_{R_k,R_k} = \overline{\gamma}_{LI} = -5$dB. Meanwhile, some parameters in general are set as follows: $r = 0.8$bps/Hz, $N = 3$ and $\delta_e^2 = 0.3$.

In Fig. 1, the effect of changing the CSI error on the SOP performance is considered. It shows the SOP for three CSI cases: perfect CSI (e.g., $\delta_e^2 = 0$), small CSI error (e.g., $\delta_e^2 = 0.01$), and large CSI error (e.g., $\delta_e^2 = 0.1$).

$$F(\alpha) = 1 - \frac{1-\delta_e^2}{\alpha\delta_e^2\overline{\gamma}_{R_k,E}} \cdot \exp\left(-\frac{\alpha-1}{(1-\delta_e^2)\overline{\gamma}_{R_k,S_2}}\right) \cdot (-\exp(\beta(\alpha)\cdot\mu(\alpha))) \cdot \mathrm{Ei}(-\beta(\alpha)\cdot\mu(\alpha)) \cdot \left(1 - \sum_{n=0}^{N}\binom{N}{n}\frac{(-1)^n}{\overline{\gamma}_{S_1,E}} \times \left(\frac{1-\delta_e^2}{\alpha\delta_e^2}\right)^n \cdot \exp\left(-\frac{k(\alpha-1)(\overline{\gamma}_{R_k,R_k}+1)}{(1-\delta_e^2)\overline{\gamma}_{S_1,R_k}}\right) \cdot \varsigma_1^{n-1}(n\alpha)\cdot\exp\left(\varsigma_1(n\alpha)\cdot\beta(\alpha)\right)\cdot\Gamma(-n+1,\varsigma_1(n\alpha)\cdot\beta(\alpha))\right) \quad (25)$$

$$F(\alpha) \approx 1 - \frac{1-\delta_e^2}{\alpha\delta_e^2\overline{\gamma}_{R_k,E}} \cdot \exp\left(-\frac{\alpha-1}{(1-\delta_e^2)\overline{\gamma}_{R_k,S_2}}\right) \cdot \frac{1}{\beta(\alpha)\cdot\mu(\alpha)} \times \left(1 - \sum_{n=0}^{N}\binom{N}{n}\frac{(-1)^n}{\overline{\gamma}_{S_1,E}} \cdot \left(\frac{1-\delta_e^2}{\alpha\delta_e^2}\right)^n \cdot \exp\left(-\frac{n(\alpha-1)(\overline{\gamma}_{R_k,R_k}+1)}{(1-\delta_e^2)\overline{\gamma}_{S_1,R_k}}\right) \cdot \frac{1}{\varsigma_1(n\alpha)\beta^n(\alpha)}\right) \quad (26)$$

$$F(\alpha) = 1 - \frac{\overline{\gamma}_{R_k,S_2}}{\alpha\overline{\gamma}_{R_k,E}+\overline{\gamma}_{R_k,S_2}} \cdot \exp\left(-\frac{\alpha-1}{\overline{\gamma}_{R_k,S_2}}\right) \times \left(1 - \sum_{n=0}^{N}\binom{N}{n}\frac{(-1)^n\overline{\gamma}_{S_1,R_k}}{n\alpha\overline{\gamma}_{S_1,E}(\overline{\gamma}_{R_k,R_k}+1)+\overline{\gamma}_{S_1,R_k}} \cdot \exp\left(-\frac{n(\alpha-1)(\overline{\gamma}_{R_k,R_k}+1)}{\overline{\gamma}_{S_1,R_k}}\right)\right) \quad (27)$$

Under the same conditions, the SOP of the system will decreases as the average SNR increases. The SOP of the perfect CSI system is always smaller than the SOP of the imperfect CSI system. As the CSI error increases, the distance between perfect and imperfect CSI curves will increases. Meanwhile, the SOP performance of the FD system is superior to the HD system. Finally, as the average SNR increases, the distance between the perfect and imperfect CSI curves becomes larger.

In Fig. 2, we analyze the impact of the number of relays on system SOP performance. The SOP performance is considered when the number of relays N varies from 1 to 10. As can be seen from Fig. 2, as the number of relay increases, the SOP of the system will decrease, and the performance of the system will become better. Meanwhile, the SOP performance is considered with different average SNRs of the eavesdropper. Three special cases are considered, i.e. $\overline{\gamma}_E = -5$dB, $\overline{\gamma}_E = -10$dB, and $\overline{\gamma}_E = -15$dB. It is observed that the emergence of high SNR eavesdroppers can erode SOP more than low SNR eavesdroppers.

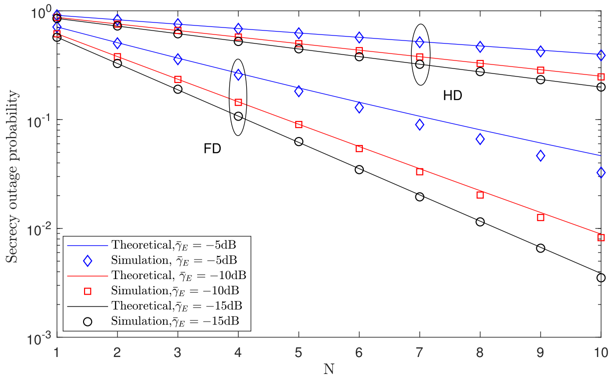


FIGURE 2. **The SOP versus the number of relays for different values of $\overline{\gamma}_E$.**

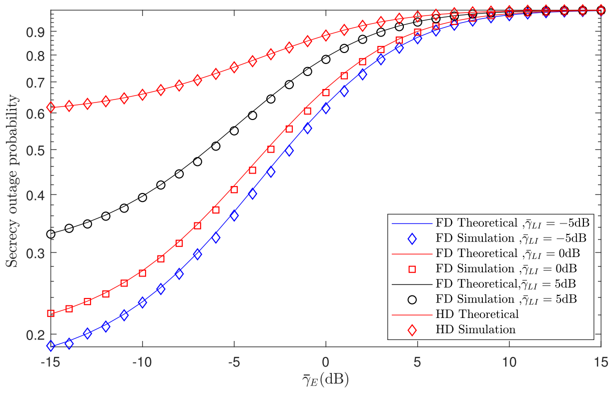


FIGURE 3. **The SOP versus the average SNR of the eavesdropper for different values of $\overline{\gamma}_{LI}$.**

In Fig. 3, we analyze the impact of the average SNR of the eavesdropper on system performance. The SOP performance is considered when the average SNR of the eavesdropper varies $\overline{\gamma}_E$ from -15dB to 15dB. As can be seen from Fig. 3, as the SNR of the eavesdropper increases, the SOP of the system will gradually increase, and the performance of the system will become worse. Meanwhile, the SOP performance is considered with different the average SNR of the residual SI. Three special cases are considered, i.e. $\overline{\gamma}_{LI} = -5$dB, $\overline{\gamma}_{LI} = 0$dB, and $\overline{\gamma}_{LI} = 5$dB. It has been observed that the SOP of the FD relay system is always lower than the SOP of the HD relay system at low the average SNR of the eavesdropper. However, in high the average SNR of the eavesdropper, when the residual SI is sufficiently large, the SOP of the FD relay system will be significantly higher than the SOP of the HD relay system.

In Fig. 4, we analyze the impact of the average SNR of the residual SI on system performance. The SOP performance is considered when the average SNR of the residual SI varies $\overline{\gamma}_{LI}$ from -5dB to 20dB. As can be seen from Fig. 4, the theoretical derivation expressions of SOP tightly matches the Monte Carlo simulation results. Further, as the average SNR of the residual SI increases, the SOP of the system will gradually increase, and the performance of the system will become worse. Meanwhile, since the HD relay system has no SI, residual SI has no effect on the SOP. Thus, three curves of HD are horizontal lines.

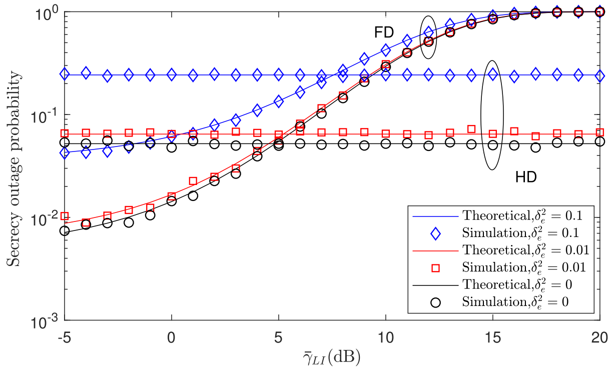


FIGURE 4. **The SOP versus the average SNR of the residual SI for different values of different CSI.**

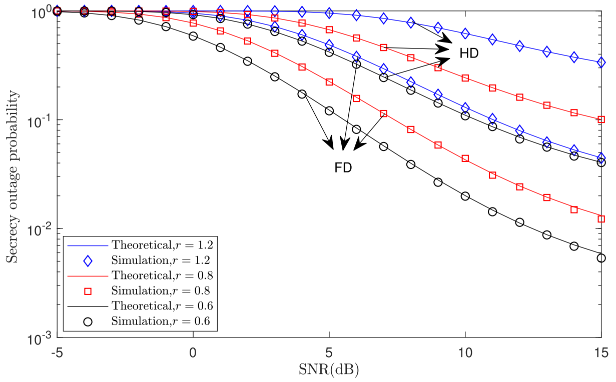


FIGURE 5. **The SOP versus the average SNR for different values of the target transmission rate.**

Fig. 5 shows the SOP vs the target transmission rate for HD and FD relay schemes, where r is set as 0.6bps/Hz, 0.8bps/Hz and 1.2bps/Hz. Both the simulation and theoretical results for the HD and FD relay schemes are presented, which are shown to be well matched. This verifies the closed-form SOPs for the HD and FD relay schemes which are given by (13) and (4) respectively. Further, the SOP is higher for larger data transmission SNR, and HD relay schemes have the worst secrecy performance.

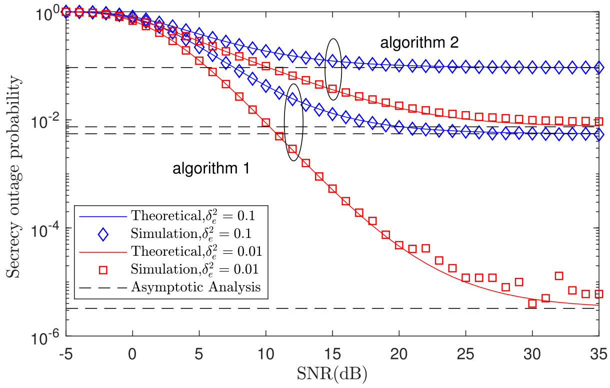


FIGURE 6. **The SOP versus different average SNRs for two relay selection schemes.**

Fig. 6 shows the SOP vs different average SNRs for FD relay system. There are two relay selection schemes, namely maximum end-to-end capacity (Algorithm 1) and partial SINR (Algorithm 2). The solid lines denote the analysis results given by (4), (16) for Algorithm 1 and (25), (26) for Algorithm 2, while markers denote the results of Monte-Carlo simulations. For two algorithms, the performance of Algorithm 1 is superior to Algorithm 2. The dashed line in the Fig. 6 represents the asymptotic result when $\overline{\gamma} \to \infty$. In the figure, we don't have the exact SOP result and the asymptotic result with $\delta_e^2 = 0$. Because its asymptotic result is close to zero, it isn't shown in the figure. Furthermore, as can be seen from the asymptotic results in the figure, the achievable secrecy diversity order is zero.

VI. CONCLUSION

In this paper, we have studied the SOP performance of a secure FD multi-relay system. Two relay selection schemes are proposed to enhance the physical-layer security of the relaying system. The first is to maximum the end-to-end instantaneous security capacity by selecting the optimal relay. The second scheme is to maximum the partial SINR with low complexity. Moreover, the SOP expressions are derived with perfect and imperfect CSI, respectively. The numerical results show that the analytical approximations closely match the Monte Carlo simulation results. As the SNR of link between the users and relays increases, the SOPs of FD system decrease. Under the same conditions, the SOP of the perfect CSI is smaller than that of the imperfect CSI. The SOPs of FD system with imperfect CSI are also related to the number of relay candidates, the SNR of the eavesdropper link, and residual SI. The proposed FD relay selection scheme is superior to the traditional HD relay selection scheme. And the scheme based on the maximum end-to-end instantaneous security capacity is superior to another one based on the maximum partial SINR. It is worth mentioning that we mainly investigated the DF relay protocol for FD relay networks in this paper. In the future, we will extend the results of this paper to other conventional schemes.

REFERENCES

[1] Y. Wu, A. Khisti, C. Xiao, G. Caire, K.-K. Wong, and X. Gao, "A survey of physical layer security techniques for 5G wireless networks and challenges ahead," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 4, pp. 679–695, Apr. 2018.

[2] A. D. Wyner, "The wire-tap channel," *Bell Syst. Tech. J.*, vol. 54, no. 8, pp. 1355–1387, 1975.

[3] D. T. Hung, T. T. Duy, and D. Q. Trinh, "Security-reliability analysis of multi-hop LEACH protocol with fountain codes and cooperative jamming," *EAI Endorsed Trans. Ind. Netw. Intell. Syst.*, vol. 6, no. 18, p. e2, Mar. 2019.

[4] V.-D. Nguyen, T. Q. Duong, O. A. Dobre, and O.-S. Shin, "Joint information and jamming beamforming for secrecy rate maximization in cognitive radio networks," *IEEE Trans. Inf. Forensics Security*, vol. 11, no. 11, pp. 2609–2623, Nov. 2016.

[5] V.-D. Nguyen, H. V. Nguyen, O. A. Dobre, and O.-S. Shin, "A new design paradigm for secure full-duplex multiuser systems," *IEEE J. Select. Areas Commun.*, vol. 36, no. 7, pp. 1480–1498, Jul. 2018.

[6] M. Zeng, N.-P. Nguyen, O. A. Dobre, and H. V. Poor, "Securing downlink massive MIMO-NOMA networks with artificial noise," *IEEE J. Sel. Topics Signal Process.*, vol. 13, no. 3, pp. 685–699, Jun. 2019.

[7] S. Q. Nguyen, H. T. Nguyen, D. D. Van, and W.-J. Hwang, "Exact outage analysis of cognitive energy harvesting relaying networks under physical layer security," *EAI Endorsed Trans. Ind. Netw. Intell. Syst.*, vol. 19, no. 18, p. e1, Mar. 2019.

[8] Y. Wu, R. Schober, D. W. K. Ng, C. Xiao, and G. Caire, "Secure massive MIMO transmission with an active eavesdropper," *IEEE Trans. Inf. Theory*, vol. 62, no. 7, pp. 3880–3900, Jul. 2016.

[9] I. Krikidis, "Opportunistic relay selection for cooperative networks with secrecy constraints," *IET Commun.*, vol. 4, no. 15, pp. 1787–1791, Oct. 2010.

[10] L. J. Rodriguez, N. H. Tran, T. Q. Duong, T. Le-Ngoc, M. Elkashlan, and S. Shetty, "Physical layer security in wireless cooperative relay networks: State of the art and beyond," *IEEE Commun. Mag.*, vol. 53, no. 12, pp. 32–39, Dec. 2015.

[11] B. Zhong and Z. Zhang, "Secure full-duplex two-way relaying networks with optimal relay selection," *IEEE Commun. Lett.*, vol. 21, no. 5, pp. 1123–1126, May 2017.

[12] A. Kuhestani, A. Mohammadi, and M. Mohammadi, "Joint relay selection and power allocation in large-scale MIMO systems with untrusted relays and passive eavesdroppers," *IEEE Trans. Inf. Forensics Security*, vol. 13, no. 2, pp. 341–355, Feb. 2018.

[13] C. Kong, C. Zhong, M. Matthaiou, E. Björnson, and Z. Zhang, "Spectral efficiency of multipair massive MIMO two-way relaying with imperfect CSI," *IEEE Trans. Veh. Technol.*, vol. 68, no. 7, pp. 6593–6607, Jul. 2019.

[14] X. Sun, K. Xu, and Y. Xu, "Performance analysis of multi-pair two-way amplify-and-forward relaying with imperfect CSI over Ricean fading channels," *IET Commun.*, vol. 12, no. 3, pp. 261–270, Feb. 2018.

[15] C. Sun, K. Liu, D. Zheng, and W. Ai, "Secure communication for two-way relay networks with imperfect CSI," *Entropy*, vol. 19, no. 10, p. 522, Sep. 2017.

[16] Q. Ding and Y. Jing, "Outage probability analysis and resolution profile design for massive MIMO uplink with mixed-ADC," *IEEE Trans. Wireless Commun.*, vol. 17, no. 9, pp. 6293–6306, Sep. 2018.

[17] H. Lei, Z. Yang, K.-H. Park, I. S. Ansari, Y. Guo, G. Pan, and M.-S. Alouini, "Secrecy outage analysis for cooperative NOMA systems with relay selection schemes," *IEEE Trans. Commun.*, to be published.

[18] S.-I. Chu, "Secrecy analysis of modify-and-forward relaying with relay selection," *IEEE Trans. Veh. Technol.*, vol. 68, no. 2, pp. 1796–1809, Feb. 2019.

[19] P. Chakraborty and S. Prakriya, "Secrecy outage performance of a cooperative cognitive relay network," *IEEE Commun. Lett.*, vol. 21, no. 2, pp. 326–329, Feb. 2017.

[20] V. N. Vo, T. G. Nguyen, C. So-In, Z. A. Baig, and S. Sanguanpong, "Secrecy outage performance analysis for energy harvesting sensor networks with a jammer using relay selection strategy," *IEEE Access*, vol. 6, pp. 23406–23419, Apr. 2018.

[21] T. Zhang, Y. Cai, Y. Huang, T. Q. Duong, and W. Yang, "Secure full-duplex spectrum-sharing wiretap networks with different antenna reception schemes," *IEEE Trans. Commun.*, vol. 65, no. 1, pp. 335–346, Jan. 2017.

[22] N.-P. Nguyen, H. Q. Ngo, T. Q. Duong, H. D. Tuan, and D. B. da Costa, "Full-duplex cyber-weapon with massive arrays," *IEEE Trans. Commun.*, vol. 65, no. 12, pp. 5544–5558, Dec. 2017.

[23] N.-P. Nguyen, C. Kundu, H. Q. Ngo, T. Q. Duong, and B. Canberk, "Secure full-duplex small-cell networks in a spectrum sharing environment," *IEEE Access*, vol. 4, pp. 3087–3099, 2016.

[24] T.-X. Zheng and H.-M. Wang, "Optimal power allocation for artificial noise under imperfect CSI against spatially random eavesdroppers," *IEEE Trans. Veh. Technol.*, vol. 65, no. 10, pp. 8812–8817, Oct. 2016.

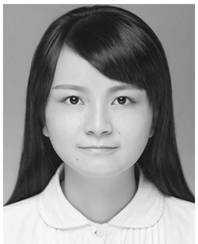
[25] H. Cui, R. Zhang, L. Song, and B. Jiao, "Relay selection for bidirectional AF relay network with outdated CSI," *IEEE Trans. Veh. Technol.*, vol. 62, no. 9, pp. 4357–4365, Nov. 2013.

[26] Y. Zou, X. Wang, and W. Shen, "Optimal relay selection for physical-layer security in cooperative wireless networks," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 10, pp. 2099–2111, Oct. 2013.

[27] D. Wang and S. Wang, "Relay selection and power allocation for full-duplex decode-and-forward relay cooperative networks," in *Proc. 24th Asia–Pacific Conf. Commun. (APCC)*, Nov. 2018, pp. 73–78.

[28] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series, and Products*, 7th ed. New York, NY, USA: Academic, 2007.

QINGFENG DING received the B.Eng. and M.Eng. degrees from East China Jiaotong University, Nanchang, Jiangxi, China, in 2002 and 2007, respectively, and the Ph.D. degree in communication and information system from Shanghai University, Shanghai, China in 2015. From 2017 to 2018, he was a Visiting Scholar with the University of Alberta, Edmonton, AB, Canada. He is currently an Associate Professor with the School of Electrical and Automation Engineering Departments, East China Jiaotong University. His research interests include massive MIMO systems, cooperative relay networks, train communication networks, and intelligent optimization.



MENGXIA LIU received the B.S. degree in electronic information engineering from East China Jiaotong University, Nanchang, China, in 2017, where she is currently pursuing the M.S. degree with the Traffic Information Engineering and Control, School of Electrical and Automation Engineering. Her research interests include cooperative relay networks and physical layer security.

YUQIAN DENG was born in Henan, China, in 1991. He received the B.S. degree in electronic information engineering from East China Jiaotong University, Nanchang, China, in 2017, where he is currently pursuing the M.S. degree with the Traffic Information Engineering and Control, School of Electrical and Automation Engineering. His research interests include mmWave communications and performance optimization in massive MIMO systems.

• • •