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Physical layer security via maximal ratio combining and relay selection over Rayleigh fading channels

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Abstract In this paper, the impact of both maximal ratio combining (MRC) and relay selection on the physical layer security in wireless communication systems is investigated by analyzing critical issues such as the probability characteristics of the legitimate receiver (Bob) and malicious eavesdropper (Eve)'s end-to-end signal-to-noise ratio (SNR), the secrecy outage probability and the average secrecy channel capacity over Rayleigh fading Channel, etc. Unlike the conventional physical layer security schemes, we assume that Bob receives its data from both the relay and the source via cooperative relay, provided that MRC is employed at the receiver. Particularly, compared to the conventional MRC methods, the proposed method is capable of achieving a higher spatial diversity order by performing relay selection, as validated by performing the theoretical analysis as well as numerical simulation. Furthermore, the closed-form expressions in terms of secrecy outage probability and average secrecy capacity are all consistent with the numerical results. Finally, the proposed scheme may be substantially affected by a number of parameters such as the number of relays, the SNR of links and the ratio of main-to-eavesdropper ratio (MER) λ_{ME}.

Keywords average secrecy capacity, cooperative communication, maximal ratio combining, outage probability, physical layer security

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1 Introduction

Cooperative communication technology has shown to be capable of substantially increasing the spectral efficiency of wireless networks, extending the radio coverage to facilitate a seamless wireless service, providing better immunity against signal fading as well as saving more system-wide power [1–10]. The cooperative communication protocols are expected to be adopted as standard in the next generation wireless communications systems such as 802.16j and the fifth-generation (5G) systems [8, 11–17].

Since wireless devices in cooperative networks are allowed to access the relay in an opportunistic manner, the devices become increasingly vulnerable to malicious attacks due to the open and dynamic

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nature of cooperative networks. The problem of physical layer security in cooperative communication systems thus becomes an important issue in facilitating a robust and secure user communication.

Physical layer security in wireless communication systems has already attracted wide attention [18–25]. Among the existing techniques, Ref. [23] presented an analytical approach to investigate the maximum transmit power constraint and interference power constraint on the secrecy in cognitive radio networks. Ref. [24] analyzed the security enhancement relying on relay selection in cognitive radio networks. Furthermore, Ref. [25] investigated the impact of both the main-to-eavesdropper ratio (MER) and the relay selection on the secrecy. Additionally, the method of increasing spatial diversity is proven to be an ideal way of effectively improving the physical layer security [26–28].

- The physical layer security in cognitive radio networks has been studied in [26], showing that the multiuser diversity gain can be significantly improved by performing multiple scheduling.
- The physical layer security in considering wiretap two-wave with diffuse power fading channels has been studied in [27], where the receiver and the eavesdropper employ maximal ratio combining (MRC) to maximize the probabilities of both the secure transmission and successful eavesdropping.

Apart from that, the performance of cooperative relay networks was studied in [29], where the multiple parallel decode-and-forward (DF) relays are assumed to be deployed. However, an orthogonal channel among relays must be allocated for mitigating the inter-relay interference in a multi-relay cooperative system, in which the operation may substantially erode the spectral utilization. Therefore, implementing relay selection would be a suitable method for optimizing the performance of the cooperative systems at a reasonable cost of channel state information (CSI) feedback.

In this paper, physical layer security in opportunistic relay selection[1] networks over independent and identically distributed (i.i.d.) Rayleigh fading channels will be studied, while considering MRC as the receiver. Compared with the existing work, the main contributions of this paper are exhibited as follows:

1. Compared with single relay scenario, physical layer security in cooperative networks with opportunistic relay selection has more benefits in terms of secure outage probability and secure channel capacity due to higher diversity being obtained by small scale fading.
2. The impact of the MER on the legitimate receiver of DF-based cooperative networks is analyzed. Furthermore, we can improve the performance in terms of secure outage probability and secure channel capacity by increasing MER.
3. The closed-form expressions for some figures of merit, including the secrecy outage probability and the average secrecy channel capacity over Rayleigh fading channels, are derived for the proposed scheme.

The remainder of this paper is organized as follows. Section 2 introduces the system model of cooperative network with an eavesdropper. The closed-form expressions for the secrecy outage probability and average secrecy capacity over Rayleigh fading channels are derived in Sections 3 and 4, respectively. Section 5 gives out the numerical results. Finally, Section 6 concludes this paper.

Notation: $f_X(.)$ and $F_X(.)$ represent the probability density function (PDF) and cumulative distribution function (CDF) of the random variable (RV) X, respectively. $\mathcal{M}_X(s)$ denotes the Moment generation function (MGF) of RV X. $\otimes$ denotes the convolution operator. $\mathrm{E}\{\cdot\}$ denotes the expectation operator.

2 System model

In this section, a cooperative network comprising a source terminal (Alice) (S), N half-duplex (HD) relay terminals (R), a malicious eavesdropper (Eve) (E), and a destination legitimate receiver (Bob) (D), is considered, as illustrated in Figure 1. All single-antenna terminals are assumed to operate in time division multiple access (TDMA) mode. In the first time slot, the source broadcasts its signal to the relays and destination. In the second time slot, on the other hand, only the selected relay will forward its received data to the destination. The opportunistic relay-selection scheme can be formulated as

$$k = \arg \max_{i:R_i \in \Omega} \min(\gamma_{SR_i}, \gamma_{R_iD}), \tag{1}$$

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[1] Basically, relays operating at either half-duplex [1] or full-duplex [30] mode can be considered. In this paper, without loss of generality, only half-duplex relays are considered.

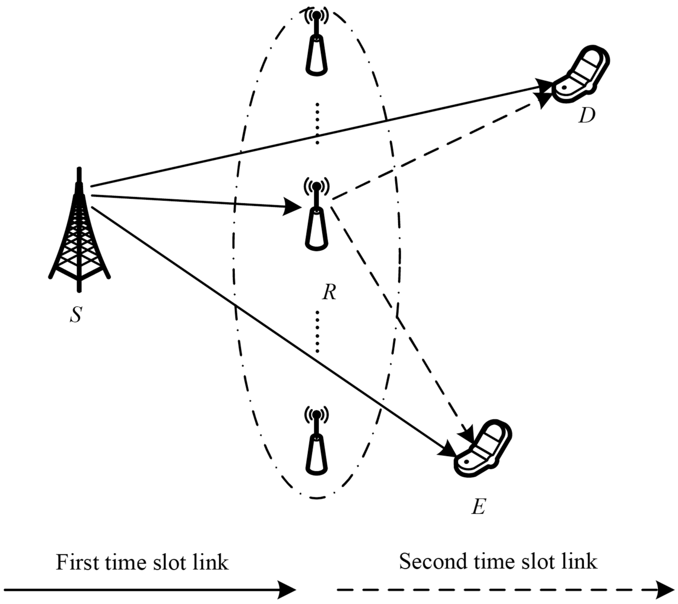


Figure 1 The system model of cooperative network having an eavesdropper.

where $\Omega = \{R_n, n = 1, 2, \ldots, N\}$ denotes the set of N half-duplex DF relays.

Without loss of generality, each link in the network is assumed to suffer from zero-mean additive white Gaussian noise (AWGN) with variance σ_0^2. Furthermore, the fading in each $a \to b$ link is assumed to be i.i.d. Rayleigh distributed RVs with (average) signal-to-noise ratio (SNR) γ_{ab} ($\bar{\gamma}_{ab}$), where $a, b \in \{S, R, D, E\}$. Therefore, the PDF and CDF of γ_{ab} can be given by $f_{\gamma_{ab}}(\gamma) = \frac{1}{\bar{\gamma}_{ab}} \mathrm{e}^{-\frac{\gamma}{\bar{\gamma}_{ab}}}$, and $F_{\gamma_{ab}}(\gamma) = 1 - \mathrm{e}^{-\frac{\gamma}{\bar{\gamma}_{ab}}}$, respectively.

3 Closed-form expression for the secrecy outage probability over Rayleigh fading channels

When the instantaneous secrecy capacity C_S drops below the expected secrecy rate r_S, the secrecy outage probability of the proposed relaying scheme over Rayleigh fading channels can be derived as [27, Eq. 35]

$$\begin{aligned} P_{\text{out}} &= \Pr\{C_S < r_S\} \\ &= \int_0^{+\infty} \int_0^{\eta(1+x)-1} f_{\gamma_{\text{Eve}}}(x) f_{\gamma_{\text{Bob}}}(y) \, \mathrm{d}y \mathrm{d}x \\ &= \int_0^{+\infty} f_{\gamma_{\text{Eve}}}(x) F_{\gamma_{\text{Bob}}}(\eta(1+x) - 1) \, \mathrm{d}x, \end{aligned} \tag{2}$$

where γ_{Eve} and γ_{Bob} denote received SNR at Eve and Bob, respectively, and $\eta = 2^{\mathcal{K}}$, in which $\mathcal{K} = 2r_S$ for the half-duplex relaying mode with two time slots.

3.1 DF protocol

In this section, both the direct $S \to D$ and $S \to E$ links are assumed to be inactivated, requiring only one decode-and-forward (DF) operation to be performed at the relay node. The cooperative link ($S \to R \to E$) SNR at Eve can thus be rewritten as

$$\gamma_{\text{Eve}}^{\text{DF}} = \min(\gamma_{SR}, \gamma_{RE}), \tag{3}$$

where γ_{SR} and γ_{RE} denote the SNR of links $S \to R$ and $R \to E$, respectively.

By denoting $\mathcal{B} = \frac{1}{\bar{\gamma}_{SR}} + \frac{1}{\bar{\gamma}_{RE}}$, and $\mathcal{D} = \frac{1}{\bar{\gamma}_{SR}} + \frac{1}{\bar{\gamma}_{RD}}$, with $\bar{\gamma}_{RD}$ denoting the average SNR of link $R \to D$, both the PDF and CDF of effective SNR at Eve and Bob can be derived as Appendix A. Furthermore, by substituting (A3) and (A4) into (2), we can rewrite the secrecy outage of the proposed DF relay scheme as

$$P_{\text{out}}^{\text{DF}} = 1 - \frac{\mathcal{B} \cdot \exp\left\{-\left(\eta - 1\right)\mathcal{D}\right\}}{\mathcal{B} + \eta\mathcal{D}}. \tag{4}$$

3.2 MRC with DF-based relaying (without relay selection)

In this section, we assume that Eve and Bob can receive data either from the direct link or via relaying link (but without performing relay selection). By considering MRC at the receiver, we can obtain the effective SNR at Eve as

$$\gamma_{\text{Eve}}^{\text{DF}-\text{MRC}} = \gamma_{\text{Eve}}^{\text{DF}} + \gamma_{SE}, \tag{5}$$

where γ_{SE} denotes the SNR of link $S \to E$.

By denoting $\mathcal{A} = \frac{1}{\bar{\gamma}_{SE}}$, and $\mathcal{G} = \frac{1}{\bar{\gamma}_{SD}}$, the PDF and CDF of effective SNR at Eve/Bob can be derived as Appendix B. Furthermore, by substituting (B5) and (B8) into (2), we can rewrite the secrecy outage of the proposed scheme as

$$\begin{aligned} P_{\text{out}}^{\text{DF-MRC}} &= 1 - \frac{\mathcal{ABD}\exp\{-\mathcal{G}(\eta-1)\}}{(\mathcal{B}+\mathcal{G}\eta)(\mathcal{D}-\mathcal{G})(\mathcal{A}+\mathcal{G}\eta)} + \frac{\mathcal{ABG}\exp\{-\mathcal{D}(\eta-1)\}}{(\mathcal{B}+\mathcal{D}\eta)(\mathcal{D}-\mathcal{G})(\mathcal{A}+\mathcal{D}\eta)} \\ &= 1 - \frac{\mathcal{AB}}{\mathcal{D}-\mathcal{G}}\left[\frac{\mathcal{D}\exp\{-\mathcal{G}(\eta-1)\}}{(\mathcal{B}+\mathcal{G}\eta)(\mathcal{A}+\mathcal{G}\eta)} - \frac{\mathcal{G}\exp\{-\mathcal{D}(\eta-1)\}}{(\mathcal{B}+\mathcal{D}\eta)(\mathcal{A}+\mathcal{D}\eta)}\right]. \end{aligned} \tag{6}$$

3.3 MRC with DF-based relay selection

In the presence of relay selection, the equivalent SNR of the selected relaying link can be represented as

$$\gamma_{eq} = \max_{R_k \in \Omega}(\min(\gamma_{SR_k}, \gamma_{R_k D})). \tag{7}$$

After performing MRC by combining both the direct and the selected links, the equivalent SNR at the destination for Bob can be represented as

$$\gamma_{\text{Bob}}^{\text{DF-Selection}} = \gamma_{SD} + \gamma_{eq}. \tag{8}$$

The PDF and CDF of effective SNR at Eve/Bob can be derived as Appendix C. By substituting (B5) and (C8) into (2), we can rewrite the secrecy outage probability of MRC with DF-based relay selection as

$$\begin{aligned} P_{\text{out}}^{\text{DF-Selection}} = \frac{\mathcal{AB}}{\mathcal{B}-\mathcal{A}} N\mathcal{D} \sum_{k=0}^{N-1} \binom{N-1}{k} \frac{(-1)^k \mathcal{G}}{\mathcal{G}-\mathcal{D}(k+1)} &\left\{\left(\frac{1}{(k+1)\mathcal{D}} - \frac{1}{\mathcal{G}}\right) \cdot \left(\frac{1}{\mathcal{A}} - \frac{1}{\mathcal{B}}\right)\right. \\ &+ \frac{1}{\mathcal{G}}\exp\left(-\mathcal{G}\left(\eta-1\right)\right)\left(\frac{1}{\mathcal{G}\eta+\mathcal{A}} - \frac{1}{\mathcal{G}\eta+\mathcal{B}}\right) \\ &\left. - \frac{1}{(k+1)\mathcal{D}}\exp\left(-\left(k+1\right)\mathcal{D}\left(\eta-1\right)\right)\left[\frac{1}{(k+1)\mathcal{D}\eta+\mathcal{A}} - \frac{1}{(k+1)\mathcal{D}\eta+\mathcal{B}}\right]\right\}. \end{aligned} \tag{9}$$

4 Closed-form expression for the average secrecy capacity over Rayleigh fading channels

In this section, the average secrecy capacity of the proposed relay scheme over Rayleigh fading channels can be given by [27, Eq. 12]

$$\mathrm{E}(C) = \frac{1}{2\ln 2}\int_0^{+\infty} \frac{F_{\gamma_{\text{Eve}}}(x)}{1+x}\left[1 - F_{\gamma_{\text{Bob}}}(x)\right] \mathrm{d}x. \tag{10}$$

Table 1 Simulation parameters for the system model

Parameter	Value
r_S	1 bps/Hz
Number of relays: N	1, 3, or 5
Power of nodes	1
Average SNR: $\bar{\gamma}_{SD}$	0, 10 dB, 15 dB, or 20 dB
Bandwidth	1 Hz
Variance of AWGN: σ_0^2	1
Average SNR: $\bar{\gamma}_{SE}, \bar{\gamma}_{RE}$	10 dB, or 15 dB
Time slots	2

4.1 DF protocol

By substituting (A2) and (A4) into (10), we can rewrite the average secrecy capacity of the proposed scheme as

$$\mathrm{E}(C^{\mathrm{DF}}) = \frac{\exp(\mathcal{G})}{2\ln 2}\left[E_1(\mathcal{G}) - \exp(\mathcal{A})\,E_1(\mathcal{A}+\mathcal{G})\right], \tag{11}$$

where $E_1(x) = \int_x^{+\infty} \mathrm{e}^{-t}/t\mathrm{d}t = -E_i(-x)$ [31, Eq. 8.211.1].

4.2 MRC with DF-based relaying (without relay selection)

By substituting (B6) and (B8) into (10), we can rewrite the average secrecy capacity of the proposed scheme as

$$\begin{aligned}\mathrm{E}(C^{\text{DF-MRC}}) = {} & \frac{1}{2(\mathcal{D}-\mathcal{G})\ln 2}\left\{\mathcal{D}\exp(\mathcal{G})\,E_1(\mathcal{G}) - \mathcal{G}\exp(\mathcal{D})\,E_1(\mathcal{D}) - \frac{1}{\mathcal{B}-\mathcal{A}}\right.\\ & \times\left[\mathcal{B}\mathcal{D}\exp(\mathcal{G}+\mathcal{A})\,E_1(\mathcal{G}+\mathcal{A}) - \mathcal{B}\mathcal{G}\exp(\mathcal{A}+\mathcal{D})\,E_1(\mathcal{A}+\mathcal{D})\right.\\ & \left.\left. - \mathcal{A}\mathcal{D}\exp(\mathcal{B}+\mathcal{G})\,E_1(\mathcal{B}+\mathcal{G}) + \mathcal{A}\mathcal{G}\exp(\mathcal{B}+\mathcal{D})\,E_1(\mathcal{B}+\mathcal{D})\right]\right\}.\end{aligned} \tag{12}$$

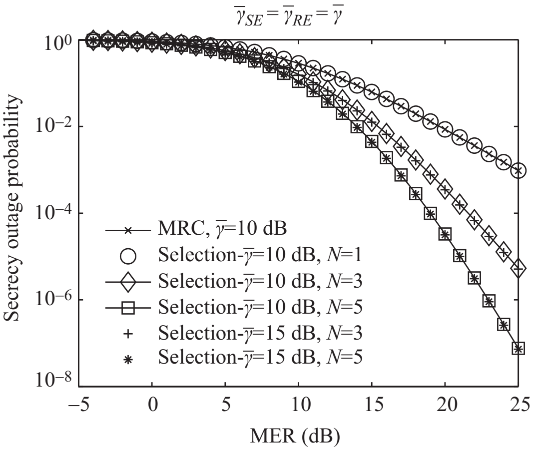
4.3 MRC with DF-based relay selection

By substituting (B6) and (C8) into (10), we can rewrite the average secrecy capacity of the proposed scheme as

$$\begin{aligned}\mathrm{E}(C^{\text{DF-Selection}}) = {} & \frac{N\mathcal{D}}{2\ln 2}\sum_{k=0}^{N-1}\binom{N-1}{k}\frac{(-1)^k\,\mathcal{G}}{\mathcal{G}-\mathcal{D}(k+1)}\left\{\frac{E_1((k+1)\,\mathcal{D})}{(k+1)\,\mathcal{D}}\exp((k+1)\,\mathcal{D})\right.\\ & - \frac{E_1(\mathcal{G})}{\mathcal{G}}\exp(\mathcal{G}) - \frac{1}{\mathcal{B}-\mathcal{A}}\left[\frac{\mathcal{B}E_1((k+1)\,\mathcal{D}+\mathcal{A})}{(k+1)\,\mathcal{D}}\exp((k+1)\,\mathcal{D}+\mathcal{A})\right.\\ & - \frac{\mathcal{B}E_1(\mathcal{G}+\mathcal{A})}{\mathcal{G}}\exp(\mathcal{G}+\mathcal{A}) - \frac{\mathcal{A}E_1((k+1)\,\mathcal{D}+\mathcal{B})}{(k+1)\,\mathcal{D}}\exp((k+1)\,\mathcal{D}+\mathcal{B})\\ & \left.\left. + \frac{\mathcal{A}E_1(\mathcal{G}+\mathcal{B})}{\mathcal{G}}\exp(\mathcal{G}+\mathcal{B})\right]\right\}.\end{aligned} \tag{13}$$

5 Numerical results

In this section, we use $\lambda_{\mathrm{ME}} = \bar{\gamma}_{SD}/\bar{\gamma}_{SE} = \bar{\gamma}_{SR}/\bar{\gamma}_{RE} = \bar{\gamma}_{RD}/\bar{\gamma}_{RE}$ to denote the MER throughput. Particularly, $\sigma_0^2 = 1$ is considered for simplicity, with $r_S = 1$bps/Hz assumed. Note that the proposed analysis is valid for the other channel parameter settings. Furthermore, the simulation parameters for the proposed system are defined in Table 1.



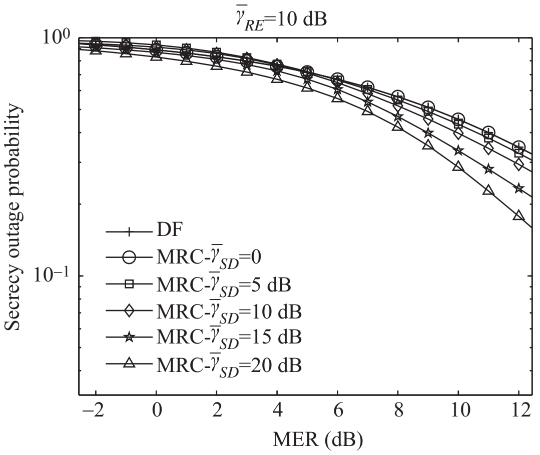
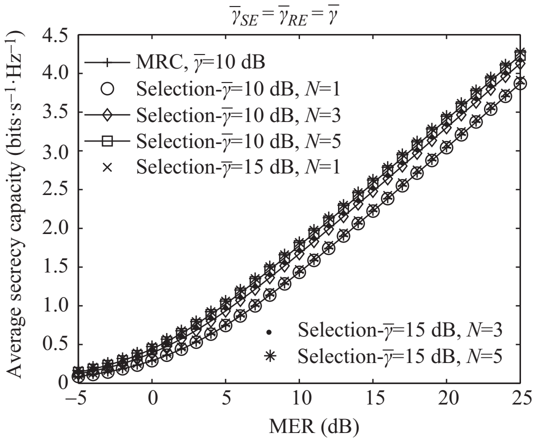


Figure 2 Secrecy outage probability versus the MER for different values of N.

Figure 3 Outage probability versus the MER for different values of the average SNR of $S \to D$ links, $\bar{\gamma}_{SD}$.



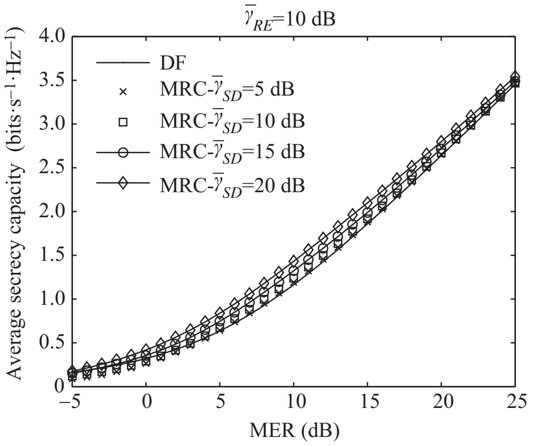


Figure 4 Secrecy average capacity versus the MER for different values of N.

Figure 5 Secrecy average capacity versus the MER for different values of the average SNR of $S \to D$ links, $\bar{\gamma}_{SD}$.

Secrecy outage probability as a function of λ_{ME} for various N values is demonstrated in Figure 2, in which we assume that $\bar{\gamma}_{SE} = \bar{\gamma}_{RE} = \bar{\gamma}$ is always valid. Using more relays implies attaining a higher probability of selecting the optimum relay under the same channel links' conditions. As expected, the curve of secrecy outage probability for relay selection with $N = 1$ is identical to the MRC scheme without considering relay selection. As shown in Figure 2, by keeping MER unchanged with the same number of candidate relays, the secrecy outage probability is kept identical to that with different values of average SNR $\bar{\gamma}$ (i.e., $\bar{\gamma}$ =10 dB, and 15 dB in this simulation). Furthermore, it has also been verified that the secrecy outage probability is independent of the parameter $\bar{\gamma}$.

Secrecy outage probability as a function of λ_{ME} for various average SNR values of $S \to D$ link is also illustrated in Figure 3, where we assume that $\bar{\gamma}_{RE}$ =10 dB. In this case, increasing $\bar{\gamma}_{SD}$ implies attaining a better channel link at Bob, accordingly reducing the outage probability. It is also shown that the DF without MRC scheme outperforms that λ_{ME} <5 dB and $\bar{\gamma}_{SD}$ <10 dB in which case Eve can obtain more benefits through MRC. Anyway, we can improve the performance of secrecy outage probability by simply increasing MER, as shown in Figures 2 and 3.

Assuming $\bar{\gamma}_{SE} = \bar{\gamma}_{RE} = \bar{\gamma}$, a larger number of N implies a higher spatial diversity, and the secrecy channel capacity therefore becomes a monotonically increasing function of N, as shown in Figure 4. Furthermore, the secrecy channel capacity becomes a monotonically increasing function of λ_{ME}. By evaluating the performance with different values of $\bar{\gamma}$, the secrecy channel capacity is shown to be slightly impacted by $\bar{\gamma}$.

Average secrecy capacity as a function of λ_{ME} for different average SNR of $S \to D$ link is illustrated in Figure 5 by considering $\bar{\gamma}_{RE}$ =10 dB. In this case, increasing $\bar{\gamma}_{SD}$ implies that a better channel link could be obtained at Bob, accordingly the average secrecy capacity is increased. Similar to the outage probability performance, the average secrecy capacity performance of the DF protocol without considering MRC outperforms that with MRC if λ_{ME} <5 dB and $\bar{\gamma}_{SD}$ <10 dB, since in this case Eve can obtain more benefits by MRC. Without loss of generality, we can also improve the performance of average secrecy capacity by simply increasing MER, as shown in Figures 4 and 5.

6 Conclusion

The impact of relay selection and MRC on the physical layer security of DF relaying based cooperative communications systems was studied. We have derived the closed-form expressions for some critical figures of merit, including the probability characteristic of the Bob and Eve's end-to-end SNR, the secrecy outage probability and the average secrecy channel capacity. Furthermore, the validity of the proposed analysis has been proven via simulations, showing that the theoretical analysis matched the corresponding numerical results well. Finally, the other parameters, including the number of relays, the MER and the SNR of links, may also substantially impact the performance of multiple-relay systems.

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Conflict of interest The authors declare that they have no conflict of interest.

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Appendix A The PDF and CDF for the equivalent received SNR for Bob and Eve under DF-relaying mode

From (3), the CDF of $\gamma_{\rm Eve}^{\rm DF}$ can be derived as

$$F_{\gamma_{\rm Eve}^{\rm DF}}(x) = 1 - \left[1 - F_{\gamma_{SR}}(x)\right] \cdot \left[1 - F_{\gamma_{RE}}(x)\right], \tag{A1}$$

where $F_{\gamma_{SR}}(x) = 1 - {\rm e}^{\frac{1}{\bar{\gamma}_{SR}}}$ and $F_{\gamma_{RE}}(x) = 1 - {\rm e}^{\frac{1}{\bar{\gamma}_{RE}}}$.

From (A1), the CDF of $\gamma_{\rm Eve}^{\rm DF}$ can be rewritten as

$$F_{\gamma_{\rm Eve}^{\rm DF}}(x) = 1 - \exp\left(-\mathcal{B}x\right). \tag{A2}$$

By taking partial derivative to (A2) with respect to x, the PDF of received SNR at Eve can be derived as

$$f_{\gamma_{\rm Eve}^{\rm DF}}(x) = \mathcal{B}\exp\left(-\mathcal{B}x\right). \tag{A3}$$

Similarly, the CDF and PDF of received SNR at legitimate receiver (Bob) are given by

$$F_{\gamma_{\rm Bob}^{\rm DF}}(x) = 1 - \exp(-\mathcal{D}x), \tag{A4}$$

and

$$f_{\gamma_{\rm Bob}^{\rm DF}}(x) = \mathcal{D}\exp\left(-\mathcal{D}x\right), \tag{A5}$$

respectively.

Appendix B The PDF and CDF for the equivalent received SNR for Bob and Eve with MRC under DF-relaying mode

Since γ_{SE} and $\gamma_{\text{Eve}}^{\text{DF}}$ are independent variables, the PDF of $\gamma_{\text{Eve}}^{\text{DF}-\text{MRC}}$ can be represented as $f_{\gamma_{\text{Eve}}^{\text{DF}-\text{MRC}}}(x) = f_{\gamma_{SE}}(x) \otimes f_{\gamma_{\text{Eve}}^{\text{DF}}}(x)$. Evidently, the convolution operation is cumbersome. In view of the fact that [2]

$$\mathcal{M}_{\gamma_{\text{Eve}}^{\text{DF}-\text{MRC}}}(s) = \mathcal{M}_{\gamma_{SE}}(s)\mathcal{M}_{\gamma_{\text{Eve}}^{\text{DF}}}(s), \tag{B1}$$

the Laplace transform of (A3) can be given by

$$\mathcal{M}_{\gamma_{\text{Eve}}^{\text{DF}}}(s) = \frac{\mathcal{B}}{s+\mathcal{B}}. \tag{B2}$$

Similarly, the PDF of γ_{SE} is given by $f_{\gamma_{SE}}(x) = \mathcal{A}\mathrm{e}^{-\mathcal{A}x}$, leading to

$$\mathcal{M}_{\gamma_{SE}}(s) = \frac{\mathcal{A}}{s+\mathcal{A}}. \tag{B3}$$

Equation (B1) can thus be rewritten as

$$\mathcal{M}_{\gamma_{\text{Eve}}^{\text{DF}-\text{MRC}}}(s) = \frac{\mathcal{A}}{s+\mathcal{A}} \cdot \frac{\mathcal{B}}{s+\mathcal{B}}. \tag{B4}$$

After performing inverse Laplace transform to (B4), the PDF of $\gamma_{\text{Eve}}^{\text{DF}-\text{MRC}}$ can be derived as

$$f_{\gamma_{\text{Eve}}^{\text{DF-MRC}}}(x) = \frac{\mathcal{A}\mathcal{B}}{\mathcal{B}-\mathcal{A}}\left[\exp\left(-\mathcal{A}x\right) - \exp\left(-\mathcal{B}x\right)\right], \tag{B5}$$

leading to

$$F_{\gamma_{\text{Eve}}^{\text{DF-MRC}}}(x) = 1 - \frac{\mathcal{B}\exp\left(-\mathcal{A}x\right) - \mathcal{A}\exp\left(-\mathcal{B}x\right)}{\mathcal{B}-\mathcal{A}}. \tag{B6}$$

Similarly, the PDF and CDF of received SNR at Bob are derived as

$$f_{\gamma_{\text{Bob}}^{\text{DF-MRC}}}(x) = \frac{\mathcal{G}\mathcal{D}}{\mathcal{D}-\mathcal{G}}\left[\exp\left(-\mathcal{G}x\right) - \exp\left(-\mathcal{D}x\right)\right], \tag{B7}$$

and

$$F_{\gamma_{\text{Bob}}^{\text{DF-MRC}}}(x) = 1 - \frac{\mathcal{D}\exp\left(-\mathcal{G}x\right) - \mathcal{G}\exp\left(-\mathcal{D}x\right)}{\mathcal{D}-\mathcal{G}}, \tag{B8}$$

respectively.

Appendix C The PDF and CDF for the equivalent received SNR for Bob and Eve with MRC under DF-based relay selection

According to (7), the CDF of γ_{eq} can be derived as [12]

$$F_{\gamma_{eq}}(x) = \left[F_{\gamma_{\text{Bob}}^{\text{DF}}}(x)\right]^{N}, \tag{C1}$$

leading to

$$\begin{aligned} f_{\gamma_{eq}}(x) &= N \cdot \left\{F_{\gamma_{\text{Bob}}^{\text{DF}}}(x)\right\}^{N-1} \cdot f_{\gamma_{\text{Bob}}^{\text{DF}}}(x) \\ &= N \cdot \left\{1 - \exp(-\mathcal{D}x)\right\}^{N-1} \mathcal{D}\exp\left(-\mathcal{D}x\right) \\ &= N\mathcal{D} \cdot \sum_{k=0}^{N-1} \binom{N-1}{k} (-1)^{k} \exp(-(k+1)\mathcal{D}). \end{aligned} \tag{C2}$$

Similarly, the PDF of $\gamma_{\text{Bob}}^{\text{DF}-\text{Selection}}$ can be represented as $f_{\gamma_{\text{Bob}}^{\text{DF}-\text{Selection}}}(x) = f_{\gamma_{SD}}(x) \otimes f_{\gamma_{eq}}(x)$. The MGF of $\gamma_{\text{Bob}}^{\text{DF}-\text{Selection}}$ can thus be given by

$$\mathcal{M}_{\gamma_{\text{Bob}}^{\text{DF}-\text{Selection}}}(s) = \mathcal{M}_{\gamma_{SD}}(s)\mathcal{M}_{\gamma_{eq}}(s), \tag{C3}$$

The Laplace transform of (C2) is then given by

$$\mathcal{M}_{\gamma_{eq}}(s) = N\mathcal{D} \cdot \sum_{k=0}^{N-1} \binom{N-1}{k} \frac{(-1)^{k}}{s+(k+1)\mathcal{D}}. \tag{C4}$$

Likewise, the PDF of γ_{SD} is given by $f_{\gamma_{SD}}(x) = \mathcal{G}\mathrm{e}^{-\mathcal{G}x}$, leading to

$$\mathcal{M}_{\gamma_{SD}}(s) = \frac{\mathcal{G}}{s+\mathcal{G}}. \tag{C5}$$

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[2] Zhong B, Zhang Z, Zhang X, et al. Partial relay selection with fixed-gain relays and outdated CSI in underlay cognitive networks. IEEE Trans Veh Technol, 2013, 62: 4696–4701.

Equation (C3) can thus be rewritten as

$$\mathcal{M}_{\gamma_{\mathrm{Bob}}^{\mathrm{DF-Selection}}}(s) = \frac{\mathcal{G}N\mathcal{D}}{s+\mathcal{G}} \cdot \sum_{k=0}^{N-1} \binom{N-1}{k} \frac{(-1)^k}{s+(k+1)\mathcal{D}}. \tag{C6}$$

After performing inverse Laplace transform on (C6), the PDF received SNR at Bob can be derived as

$$f_{\gamma_{\mathrm{Bob}}^{\text{DF-Selection}}}(x) = N\mathcal{D} \sum_{k=0}^{N-1} \binom{N-1}{k} \frac{(-1)^k \mathcal{G}}{\mathcal{G}-\mathcal{D}(k+1)} \left[\exp\left(-\left(k+1\right)\mathcal{D}x\right) - \exp\left(-\mathcal{G}x\right)\right], \tag{C7}$$

leading to

$$\begin{aligned} F_{\gamma_{\mathrm{Bob}}^{\text{DF-Selection}}}(x) = N\mathcal{D} \sum_{k=0}^{N-1} \binom{N-1}{k} \frac{(-1)^k \mathcal{G}}{\mathcal{G}-\mathcal{D}(k+1)} &\left[\frac{1}{\left(k+1\right)\mathcal{D}} - \frac{1}{\mathcal{G}} + \frac{1}{\mathcal{G}}\exp\left(-\mathcal{G}x\right)\right. \\ &\left. -\frac{1}{\left(k+1\right)\mathcal{D}}\exp\left(-\left(k+1\right)\mathcal{D}x\right)\right]. \end{aligned} \tag{C8}$$

Consequently, the PDF and CDF of SNR received at Eve can be derived as (B5) and (B8), respectively.