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Research Article

Security-Reliability Tradeoff Analysis in Multisource Multirelay Cooperative Networks with Multiple Cochannel Interferers

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Cooperative relaying communication is one of the green communication technologies since it shortens the communication distance and saves the transmit power. In this paper, the physical-layer security (PLS) of a multisource multirelay cooperative relaying communication network is investigated by considering the influence of cochannel interference from a security-reliability tradeoff (SRT) perspective. First, the SRT performance is characterized by the outage probability (OP) and the intercept probability (IP). In particular, the IP encountered at the eavesdropper is used to evaluate the security performance, while the reliability performance is analyzed in terms of the OP experienced at the destination. Then, under the impact of multiple cochannel interferers, the intercept probabilities and the outage probabilities of both the conventional direct transmission (DT) strategy and relay selection (RS) strategy are derived in closed-form expressions over Rayleigh fading channels, respectively. Simulation results are provided to validate the theoretical analysis. It is shown that when the OP (reliability) requirement is relaxed, the IP (security) performance improves and vice versa. It confirms that there is an SRT existing between the OP and the IP. Meanwhile, a better SRT performance can be achieved by increasing the number of sources, relays, and cochannel interferers. In addition, it is also shown that the RS strategy generally outperforms the conventional DT strategy in terms of the product of the IP and the OP.

1. Introduction

With an explosive growth of the number of wireless devices, such as smart phones, tablet computers, and wireless sensors, more and more energy has been consumed by wireless services. According to [1], the amount of the energy consumed by the information and communication technologies accounts for about 2% to 10% of the global energy consumption, which generate nonnegligible amount of the greenhouse gases. What is worst, this percentage will grow rapidly with the development of the information and communication technologies and the increase of number of wireless devices. It will result in more greenhouse gases emission and environment pollution [2]. One promising technique to alleviate such issue is to adopt green communication technology, which can improve both the spectrum efficiency and energy efficiency of wireless communication systems. Cooperative relaying communication is an energy efficient diversity technique, which has been recognized as a green communication technology and attracts unprecedented research interest in both academic and industrial fields. A challenging issue in cooperative relaying communication is wireless security [3–5]. Because of the inherent broadcast nature of wireless channels, the destination may not successfully obtain source information, while the malicious eavesdropper may overhear and intercept the confidential information, which makes the wireless transmission insecure and vulnerable to eavesdropping attacks [6].

Motivated by the above fact, physical-layer security (PLS) was proposed and has attracted increasing research attention since it is an effective paradigm of achieving information-theoretic security for protecting wireless communications against the eavesdropping attacks by utilizing the physical characteristics of wireless channels [7]. The PLS was first investigated by Shannon [8] and further developed by Wyner, who examined a classical point-to-point discrete memoryless wiretap channel (WTC) scenario consisting of a source node and a destination node as well as an eavesdropper node [9]. It

was proven in [9] that perfectly secure and reliable transmission from the source node to the legitimate destination node can be achieved when the main channel from the source node to the destination node is an upgraded version of the wiretap channel from the source node to the eavesdropper node. Later on, in [10, 11], Wyner's conclusions were, respectively, extended from the discrete memoryless wiretap channel to the nondegraded wiretap channel and the Gaussian degraded wiretap channel, where the notion of secrecy capacity (SC) was introduced. It was derived as the difference between the channel capacity of the legitimate link and that of the wiretap link. Specifically, the SC can make the transmission from the source node to the legitimate destination node secure while achieving zero mutual information between the source node and malicious eavesdropper node. Based on this idea, extensive research efforts have been devoted to improving the SC from an information-theoretic perspective under different scenarios, for example, cooperative relaying [12–15] and beamforming techniques [16, 17], cooperative jamming (CJ) methods [18–20], and multiple-input multiple-output (MIMO) schemes [21, 22].

The previous works are mainly focused on enhancing wireless security without paying much attention to communication reliability. Hence, security-reliability tradeoff (SRT) was proposed to make best tradeoff between the outage probability (OP) and the intercept probability (IP). In particular, the IP encountered at the eavesdropper is used to evaluate the security performance, while the reliability performance is measured by the OP experienced at the destination. In [23], the authors studied the employment of various block cipher encryption algorithms from the perspective of both reliability and security and showed that there exists a tradeoff between communication reliability and security. Later on, the authors of [24] investigated the SRT for the downlink cloud radio access networks and the channel estimation errors were considered and the impact of the times of training on the security and reliability performance was also analyzed. The SRT of the cognitive amplify-and-forward (AF) relay network was investigated under imperfect channel estimation in [25]. As a further development, the authors of [26] characterized the SRT and quantified the benefits of opportunistic relay selection (ORS) for the purpose of improving the SRT. In [27], the authors proposed the single-relay and multirelay selection schemes for improving the SRT of general wireless networks. It was proved in [27] that in terms of the SRT the multirelay selection scheme outperformed the single-relay one.

It can been seen from the above works that the PLS of multisource multirelay cooperative networks under the impact of the cochannel interferers is not considered. Motivated by this fact, the main contributions of this paper are summarized as follows: firstly, the PLS of a multisource multirelay cooperative communication network is investigated from an SRT perspective and cochannel interferers are considered. Secondly, a signal-to-interference-plus-noise ratio- (SINR-) based method is proposed and the closed-form expressions of IP and OP are derived for the direct transmission (DT) and the relay selection (RS) schemes over Rayleigh fading, respectively. Finally, simulation results are provided to validate the theoretical analysis. It is shown that when the OP (reliability) requirement is relaxed, the IP (security) performance improves and vice versa. It confirms that there is an SRT existing between the OP and the IP. Meanwhile, a better SRT performance can be achieved by increasing the number of sources, relays, and cochannel interferers. In addition, it is also shown that the RS strategy generally outperforms the conventional DT strategy in terms of the product of the IP and the OP.

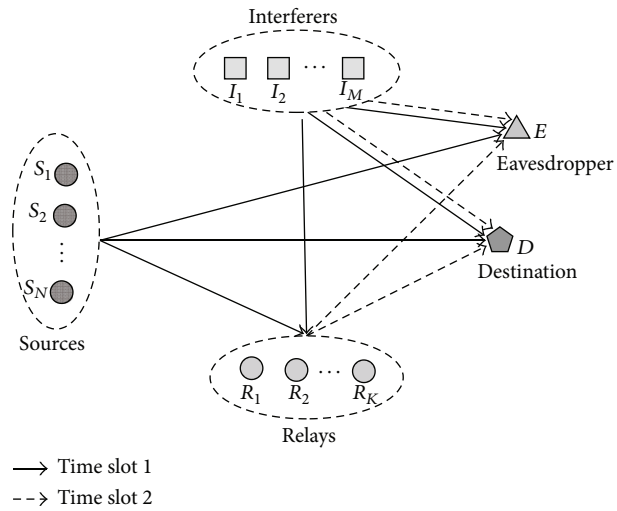

Figure 1: Multisource multirelay cooperative network system model.

The remainder of this paper is organized as follows. In Section 2, the system models are described. The SRT performance analysis for both the conventional DT and RS schemes over Rayleigh fading channels is presented in Section 3. Section 4 presents simulation results to corroborate the proposed studies. Section 5 concludes the paper.

2. The System Model

2.1. System Model Description. Consider a multisource multirelay cooperative wireless network as shown in Figure 1, which consists of N sources S_n ($1 \leqslant n \leqslant N$), one eavesdropper E, one destination D, K relays R_k ($1 \leqslant k \leqslant K$), and M cochannel interferers I_m ($1 \leqslant m \leqslant M$). The sources communicate with the corresponding destination via the direct link or with the help of the intermediate relays. At a specific time, only the source having the highest direct-link channel quality is viewed as the best one and is selected to transmit with the aid of relays. Meanwhile, E will intercept the information from the selected source and relays. M interferers share the same bands with D and E and cause interferences to them. It can be observed that the system model is practical and can be applied to practical scenarios [28–30]. It is assume that all nodes are equipped with single antenna and all channels are Rayleigh fading. Without loss of generality, we consider additive white Gaussian noise (AWGN) with zero mean and variance N_0 at each node in networks. We assume that the sources have the global channel state information (CSI) of both the main and wiretap

channels and in order to analyze the performance of the worst case, E is assumed to know all system parameters of the legitimate transmission from S to D, except for the signal. Typically, the linear minimum mean-square error (LMMSE) estimation method can be used to obtain the CSI by the destination and the eavesdropper [24, 25]. Note that this assumption has been widely used in [26, 27, 31].

2.2. Direct Transmission Strategy. In this subsection, the conventional DT strategy is considered for the purpose of performance comparison. A classical DT communication scenario consisting of N sources, one destination, and one eavesdropper with M cochannel interferers is considered. Assuming that all sources send messages at a power P_S while the interferers transmit at a power P_I. Let x_b ($E[|x_b|^2] = 1$) and x_m ($E[|x_m|^2] = 1$), respectively, denote the source signal from the selected best source S_b and the interfering signal transmitted by the mth interferer I_m. When S_b transmits x_b with the rate R_s at a particular time instant, I_m transmits x_m with the rate R_s. Hence, under the presence of M cochannel interferers, the signals received at D and E nodes can be, respectively, presented as

$$y_{S_bD}^{\mathrm{DT}} = \sqrt{P_S} h_{S_bD} x_b + \sum_{m=1}^{M} \sqrt{P_I} h_{I_mD} x_m + n_D, \tag{1}$$

$$y_{S_bE}^{\mathrm{DT}} = \sqrt{P_S} h_{S_bE} x_b + \sum_{m=1}^{M} \sqrt{P_I} h_{I_mE} x_m + n_E, \tag{2}$$

where h_{S_bD}, h_{S_bE}, h_{I_mD}, and h_{I_mE}, respectively, denote the fading gains of the channel from S_b to D, that from S_b to E, that from I_m to D, and that from I_m to E. n_D and n_E represent the AWGN encountered at D and E nodes, respectively. Using Shannon's capacity formula, the capacity of the channel spanning from S_b to D is given by

$$C_{S_bD}^{\mathrm{DT}} = \log_2\left(1 + \frac{\gamma_S \left|h_{S_bD}\right|^2}{\sum_{m=1}^{M} \gamma_I \left|h_{I_mD}\right|^2 + 1}\right), \tag{3}$$

where $\gamma_S = P_S/N_0$ and $\gamma_I = P_I/N_0$. Similarly, the channel capacity of S_b-E transmission is obtained from (2) as

$$C_{S_bE}^{\mathrm{DT}} = \log_2\left(1 + \frac{\gamma_S \left|h_{S_bE}\right|^2}{\sum_{m=1}^{M} \gamma_I \left|h_{I_mE}\right|^2 + 1}\right). \tag{4}$$

Since fading gains h_{S_bD}, h_{S_bE}, h_{I_mD}, and h_{I_mE} are modeled as Rayleigh random variables, then $|h_{S_bD}|^2$, $|h_{S_bE}|^2$, $|h_{I_mD}|^2$, and $|h_{I_mE}|^2$ are exponentially distributed. Accordingly, $\sigma_{S_bD}^2$, $\sigma_{S_bE}^2$, $\sigma_{I_mD}^2$, and $\sigma_{I_mE}^2$ represent the means of $|h_{S_bD}|^2$, $|h_{S_bE}|^2$, $|h_{I_mD}|^2$, and $|h_{I_mE}|^2$, respectively.

2.3. Relay Selection Strategy. As shown in Figure 1, this subsection presents a multisource multirelay cooperative wireless network with multiple cochannel interferers existing at relays, D and E. Specifically, all sources share the relay nodes and the relays employ the decode-and-forward (DF) relaying protocol. Without loss of generality, the total cooperative communication procedure is divided into two time slots. It can also be seen from Figure 1 that the solid and dash lines represent the transmission in the first time slot and that in the second time slot, respectively. In the first time slot, the selected best source node S_b transmits its signals x_b to D and all relays, and meanwhile E intercepts the transmission of the source. Under the presence of M cochannel interferers, the signals received at D, E, and R_k nodes can be, respectively, presented as

$$y_{S_bD}^{\mathrm{RS}} = \sqrt{P_S} h_{S_bD} x_b + \sum_{m=1}^{M} \sqrt{P_I} h_{I_mD} x_m + n_D, \tag{5}$$

$$y_{S_bE}^{\mathrm{RS}} = \sqrt{P_S} h_{S_bE} x_b + \sum_{m=1}^{M} \sqrt{P_I} h_{I_mE} x_m + n_E, \tag{6}$$

$$y_{S_bR_k}^{\mathrm{RS}} = \sqrt{P_S} h_{S_bR_k} x_b + \sum_{m=1}^{M} \sqrt{P_I} h_{I_mR_k} x_m + n_{R_k}, \tag{7}$$

where $h_{S_bR_k}$ and $h_{I_mR_k}$, respectively, denote the fading gains of the channel from S_b to R_k and that from I_m to R_k. n_{R_k} represents the AWGN encountered at R_k node. Similar to [7], according to (5), (6), and (7), the capacities of the channel spanning from S_b to D, that spanning from S_b to R_k, and that spanning from S_b to E can, respectively, be obtained as

$$C_{S_bD}^{\mathrm{RS}} = \frac{1}{2}\log_2\left(1 + \frac{\gamma_S \left|h_{S_bD}\right|^2}{\sum_{m=1}^{M} \gamma_I \left|h_{I_mD}\right|^2 + 1}\right), \tag{8}$$

$$C_{S_bR_k}^{\mathrm{RS}} = \frac{1}{2}\log_2\left(1 + \frac{\gamma_S \left|h_{S_bR_k}\right|^2}{\sum_{m=1}^{M} \gamma_I \left|h_{I_mR_k}\right|^2 + 1}\right), \tag{9}$$

$$C_{S_bE}^{\mathrm{RS}} = \frac{1}{2}\log_2\left(1 + \frac{\gamma_S \left|h_{S_bE}\right|^2}{\sum_{m=1}^{M} \gamma_I \left|h_{I_mE}\right|^2 + 1}\right), \tag{10}$$

where 1/2 arises from the fact that two orthogonal slots are needed for completing the overall transmission. Similarly, $|h_{S_bR_k}|^2$ and $|h_{I_mR_k}|^2$ are exponentially distributed and accordingly, and $\sigma_{S_bR_k}^2$ and $\sigma_{I_mR_k}^2$ represent the means of $|h_{S_bR_k}|^2$ and $|h_{I_mR_k}|^2$, respectively.

According to the DF protocol, only those relays that succeed in perfectly decoding the source signal x_b form a decoding set denoted by $\mathscr{D}$. Thus, in the second time slot, when $\mathscr{D}$ is a nonempty set, a specific relay is chosen from $\mathscr{D}$ for forwarding its received signal to D node with P_S denoting the transmit power. In particular, R_k is regarded as the selected relay node. Then, the signal received at D node can be presented as

$$y_{R_kD}^{\mathrm{RS}} = \sqrt{P_S} h_{R_kD} x_b + \sum_{m=1}^{M} \sqrt{P_{I_m}} h_{I_mD} x_m + n_D, \tag{11}$$

where h_{R_kD} represents the fading gain of the channel from R_k to D. Similarly, according to (11), the capacity of the channel spanning from R_k to D is given by

$$C_{R_kD}^{\mathrm{RS}} = \frac{1}{2}\log_2\left(1 + \frac{\gamma_S \left|h_{R_kD}\right|^2}{\sum_{m=1}^{M}\gamma_I \left|h_{I_mD}\right|^2 + 1}\right), \tag{12}$$

where $|h_{R_kD}|^2$ is exponentially distributed and $\sigma_{R_kD}^2$ represents the mean of $|h_{R_kD}|^2$. Based on the obtained capacity of the channel spanning from R_k to D, the selected relay node with the largest channel capacity is chosen from $\mathscr{D}$, that is,

$$\mathsf{R}_{\mathrm{best}} = \arg\max_{\mathsf{R}_k\in\mathscr{D}} C_{R_kD}^{\mathrm{RS}}, \tag{13}$$

where $\mathsf{R}_{\mathrm{best}}$ represents the selected best relay node. It can be seen from (12) that the interferers and noise terms are same for the channel capacities of different relays. Then, (13) is simplified as $\mathsf{R}_{\mathrm{best}} = \arg\max_{\mathsf{R}_k\in\mathscr{D}}|h_{R_kD}|^2$. Thus, the signal received at E node with the best relay node can be presented as

$$y_{R_{\mathrm{best}}E}^{\mathrm{RS}} = \sqrt{P_S}h_{R_{\mathrm{best}}E}x_b + \sum_{m=1}^{M}\sqrt{P_{I_m}}h_{I_mE}x_m + n_E, \tag{14}$$

where $h_{R_{\mathrm{best}}E}$ denotes the fading gain of the channel from $\mathsf{R}_{\mathrm{best}}$ to E. Thus, according to (14), the capacity of the channel spanning from $\mathsf{R}_{\mathrm{best}}$ to E is given by

$$C_{R_{\mathrm{best}}E}^{\mathrm{RS}} = \frac{1}{2}\log_2\left(1 + \frac{\gamma_S \left|h_{R_{\mathrm{best}}E}\right|^2}{\sum_{m=1}^{M}\gamma_I \left|h_{I_mE}\right|^2 + 1}\right), \tag{15}$$

where $|h_{R_{\mathrm{best}}E}|^2$ is exponentially distributed and $\sigma_{R_{\mathrm{best}}E}^2$ represents the mean of $|h_{R_{\mathrm{best}}E}|^2$.

Across this paper, for ease of discussion, we assume that $\sigma_{S_bD}^2 = \sigma_{S_bR_k}^2 = \sigma_{R_kD}^2 = \sigma_S^2$, $\sigma_{S_bE}^2 = \sigma_{R_{\mathrm{best}}E}^2 = \sigma_E^2$ and $\sigma_{I_mR_k}^2 = \sigma_{I_mD}^2 = \sigma_{I_mE}^2 = \sigma_I^2$. This assumption can be valid in a statistical sense when all relays are mobile and uniformly distributed around S and D nodes [7].

3. SRT Performance Analysis over Rayleigh Fading Channels

In this section, the SRT performance analysis of the conventional DT strategy as well as of the RS strategy with the presence of multiple cochannel interferers communicating over Rayleigh fading channels is presented. As discussed in [7], the tradeoff between the security and reliability, characterized by the intercept probability and by the outage probability, is analyzed. In particular, the outage probability represents the probability that the capacity of the main channel is lower than the data rate and the intercept probability represents the probability that the capacity of the wiretap channel is higher than the data rate. Then, the two performance metrics can be expressed as

$$P_{\mathrm{out}} = \Pr\left(C_d < R_s\right), \tag{16}$$

$$P_{\mathrm{int}} = \Pr\left(C_e > R_s\right), \tag{17}$$

where C_d and C_e represent, respectively, the capacity of the main channel achieved at the destination and that of the wiretap channel experienced by the eavesdropper. R_s is the data rate.

3.1. Direct Transmission Strategy. In what follows, the SRT performance of the conventional DT strategy is first analyzed as a benchmark. According to (16), using the law of total probability, the OP of the conventional DT strategy can be formulated as

$$\begin{aligned} P_{\mathrm{out}}^{\mathrm{DT}} &= \sum_{b=1}^{N}\Pr\left(\left|h_{S_bD}\right|^2 > \max_{1\leqslant n\leqslant N, n\neq b}\left(\left|h_{S_nD}\right|^2\right),\ C_{S_bD}^{\mathrm{DT}} < R_s\right), \end{aligned} \tag{18}$$

where $C_{S_bD}^{\mathrm{DT}}$ is given by (3). Substituting $C_{S_bD}^{\mathrm{DT}}$ into (18), the OP is given by

$$\begin{aligned} P_{\mathrm{out}}^{\mathrm{DT}} &= \sum_{b=1}^{N}\underbrace{\Pr\left(\left|h_{S_bD}\right|^2 > \max_{1\leqslant n\leqslant N, n\neq b}\left(\left|h_{S_nD}\right|^2\right),\ \frac{\gamma_S\left|h_{S_bD}\right|^2}{Y+1} < \Delta\right)}_{P_1}, \end{aligned} \tag{19}$$

where $Y = \sum_{m=1}^{M}\gamma_I|h_{I_mD}|^2$ and $\Delta = (2^{R_s} - 1)$. Note that, due to the common term $|h_{S_bD}|^2$, P_1 cannot be calculated as the conventional analysis directly. Hence, upon assuming $|h_{S_bD}|^2 = x$, P_1 can be expressed as

$$\begin{aligned} P_1 = \int_0^{\infty}&\Pr\left(\max_{1\leqslant n\leqslant N, n\neq b}\left(\left|h_{S_nD}\right|^2\right) < x \mid x\right) \\ &\times \Pr\left(\frac{\gamma_S x}{Y+1} < \Delta \mid x\right) f_{|h_{S_bD}|^2}(x)\,dx, \end{aligned} \tag{20}$$

in which the first term can be obtained as

$$\begin{aligned} &\Pr\left(\max_{1\leqslant n\leqslant N, n\neq b}\left(\left|h_{S_nD}\right|^2\right) < x \mid x\right) \\ &\quad= \prod_{1\leqslant n\leqslant N, n\neq b}\Pr\left(\left|h_{S_nD}\right|^2 < x \mid x\right) \\ &\quad= \sum_{n=0}^{N-1}C_{N-1}^{n}(-1)^n\exp\left(-\frac{nx}{\sigma_{S_nD}^2}\right). \end{aligned} \tag{21}$$

In (20), it can be found that, for $x < \Delta/\gamma_S$, the second-term $\Pr(\gamma_S x/(Y+1) < \Delta \mid x) = 1$. Therefore, there are two cases for the term $\Pr(\gamma_S x/(Y+1) < \Delta \mid x)$; that is,

$$\Pr\left(\frac{\gamma_S x}{Y+1} < \Delta \mid x\right) = \begin{cases} 1 & x < \dfrac{\Delta}{\gamma_S} \\ \exp\left(\dfrac{\Delta - \gamma_S x}{\gamma_I\sigma_{I_mD}^2\Delta}\right)\displaystyle\sum_{m_1=0}^{M-1}\frac{\left(\left(\gamma_S x - \Delta\right)/\gamma_I\sigma_{I_mD}^2\Delta\right)^{m_1}}{m_1!} & x > \dfrac{\Delta}{\gamma_S}. \end{cases} \tag{22}$$

Then substituting (21) and (22) into (20) yields

$$\begin{aligned} P_1 = \Bigg[& \int_0^{\Delta/\gamma_S} \sum_{n=0}^{N-1} C_{N-1}^n (-1)^n \exp\left(-\frac{nx}{\sigma_{S_nD}^2}\right) \\ & + \int_{\Delta/\gamma_S}^{\infty} \sum_{n=0}^{N-1} C_{N-1}^n (-1)^n \exp\left(-\frac{nx}{\sigma_{S_nD}^2}\right) \\ & \times \exp\left(\frac{1}{\gamma_I \sigma_{I_mD}^2} - \frac{\gamma_S x}{\gamma_I \sigma_{I_mD}^2 \Delta}\right) \\ & \times \sum_{m_1=0}^{M-1} \frac{\left(\gamma_S x/\gamma_I \sigma_{I_mD}^2 \Delta - 1/\gamma_I \sigma_{I_mD}^2\right)^{m_1}}{m_1!} \Bigg] \\ & \cdot f_{|h_{S_bD}|^2}(x)\, dx. \end{aligned} \tag{23}$$

Proceeding as in Appendix A, one has

$$\begin{aligned} P_1 = \sum_{n=0}^{N-1} C_{N-1}^n (-1)^n \Bigg[& \frac{1 - \exp\left(-(n+1)\Delta/\sigma_S^2 \gamma_S\right)}{n+1} \\ & + \sum_{m_1=0}^{M-1} \exp\left(-\frac{(n+1)\Delta}{\gamma_S \sigma_S^2}\right) \\ & \cdot \frac{\gamma_I \sigma_I^2 \Delta}{\sigma_S^2 \gamma_S \left((n+1)\gamma_I \sigma_I^2 \Delta/\sigma_S^2 \gamma_S + 1\right)^{m_1+1}} \Bigg]. \end{aligned} \tag{24}$$

Similarly, according to (4) and (17), the IP of the conventional DT strategy is formulated as

$$\begin{aligned} & P_{\text{int}}^{\text{DT}} \\ & = \sum_{b=1}^{N} \Pr\left(\left|h_{S_bD}\right|^2 > \max_{1 \leqslant n \leqslant N, n \neq b} \left(\left|h_{S_nD}\right|^2\right),\ C_{S_bE}^{\text{DT}} > R_s\right). \end{aligned} \tag{25}$$

With the aid of $C_{S_bE}^{\text{DT}}$, the IP can be expressed as

$$\begin{aligned} & P_{\text{int}}^{\text{DT}} \\ & = \sum_{b=1}^{N} \underbrace{\Pr\left(\left|h_{S_bD}\right|^2 > \max_{1 \leqslant n \leqslant N, n \neq b} \left(\left|h_{S_nD}\right|^2\right),\ \frac{\gamma_S \left|h_{S_bE}\right|^2}{T+1} > \Delta\right)}_{P_2}, \end{aligned} \tag{26}$$

where $T = \sum_{m=1}^{M} \gamma_I |h_{I_mE}|^2$. Similar to the analysis of P_1, P_2 can be rewritten as

$$\begin{aligned} P_2 = \int_0^{\infty} & \Pr\left(\max_{1 \leqslant n \leqslant N, n \neq b} \left(\left|h_{S_nD}\right|^2\right) < x \mid x\right) \\ & \times \Pr\left(\frac{\gamma_S \left|h_{S_bE}\right|^2}{T+1} > \Delta \mid x\right) f_{|h_{S_bD}|^2}(x)\, dx, \end{aligned} \tag{27}$$

where the term $\Pr(\gamma_S |h_{S_bE}|^2/(T+1) > \Delta \mid x)$ can be readily derived as

$$\begin{aligned} & \Pr\left(\frac{\gamma_S \left|h_{S_bE}\right|^2}{T+1} > \Delta \mid x\right) \\ & = \exp\left(-\frac{\Delta}{\gamma_S \sigma_{S_bE}^2}\right) \frac{\left(\sigma_{S_bE}^2\right)^M}{\left(\sigma_{S_bE}^2 + \gamma_I \sigma_{I_mE}^2 \Delta/\gamma_S\right)^M}. \end{aligned} \tag{28}$$

Then substituting (21) and (28) into (27), one has

$$\begin{aligned} P_2 = \int_0^{\infty} & \sum_{n=0}^{N-1} C_{N-1}^n (-1)^n \exp\left(-\frac{nx}{\sigma_{S_nD}^2}\right) \\ & \times \exp\left(-\frac{\Delta}{\gamma_S \sigma_{S_bE}^2}\right) \frac{\left(\sigma_{S_bE}^2\right)^M}{\left(\sigma_{S_bE}^2 + \gamma_I \sigma_{I_mE}^2 \theta/\gamma_S\right)^M} \\ & \times f_{|h_{S_bD}|^2}(x)\, dx. \end{aligned} \tag{29}$$

After some appropriate incorporations and necessary mathematical manipulations, P_2 can be obtained as

$$P_2 = \sum_{n=0}^{N-1} \frac{C_{N-1}^n (-1)^n \left(\sigma_E^2\right)^M}{(n+1)\left(\sigma_E^2 + \gamma_I \sigma_I^2 \Delta/\gamma_S\right)^M} \exp\left(-\frac{\Delta}{\gamma_S \sigma_E^2}\right). \tag{30}$$

3.2. Relay Selection Strategy. This subsection focuses on the SRT performance analysis of the RS strategy. According to (16) and using the theory of total probability, the OP of the RS strategy is formulated as

$$P_{\text{out}}^{\text{RS}} = \sum_{b=1}^{N} \sum_{k=0}^{K} \sum_{\mathscr{D} \subset \mathbb{R}} \Pr\left(|\mathscr{D}| = k,\ C_D^{\text{RS}} < R_s\right), \tag{31}$$

where $|\mathscr{D}|$ represents the number of elements in successful decoding set $\mathscr{D}$ and $\mathbb{R} = \{\mathsf{R}_1, \mathsf{R}_2, \ldots, \mathsf{R}_K\}$ denotes the relay set. As can be observed, when $\mathscr{D}$ is an empty set (i.e., $|\mathscr{D}| = 0$), it shows that no relay can be chosen for forwarding the received signal. In this case, only the direct link is available, that is, $C_D^{\text{RS}} = C_{S_bD}^{\text{RS}}$, where $\mathscr{D}$ is a nonempty set and selection combining is considered to combine the received signal copies at D from the selected best source S_b and the selected best relay R_{best} during the two time slots. In this case, the capacity achieved by D is the higher one between $C_{S_bD}^{\text{RS}}$ and $C_{R_{\text{best}}D}^{\text{RS}}$, that is, $C_D^{\text{RS}} = \max(C_{S_bD}^{\text{RS}}, C_{R_{\text{best}}D}^{\text{RS}})$. Substituting these results into (31), one has

$$P_{\text{out}}^{\text{RS}} = \sum_{b=1}^{N} \left[\Pr(\mathscr{D} = \emptyset) P_3 + \sum_{k=1}^{K} \sum_{\mathscr{D} \subset \mathbb{R}} \Pr(|\mathscr{D}| = k) P_4\right], \tag{32}$$

where the terms P_3 and P_4 are, respectively, given by

$$P_3 = \Pr\left(\left|h_{S_bD}\right|^2 > \max_{1 \leqslant n \leqslant N, n \neq b} \left(\left|h_{S_nD}\right|^2\right), C_{S_bD}^{\text{RS}} < R_s\right), \tag{33}$$

$$P_4 = \Pr\left(\left|h_{S_bD}\right|^2 > \max_{1 \leqslant n \leqslant N, n \neq b} \left(\left|h_{S_nD}\right|^2\right), C_D^{\text{RS}} < R_s\right). \tag{34}$$

In (32), the term $\Pr(|\mathscr{D}| = k)$ denotes the probability that there exist k relays decoding the source signal x_s successfully. Thus, considering $\sigma^2_{S_bR_i} = \sigma^2_{S_bR_j} = \sigma^2_S$ and $\sigma^2_{I_mR_i} = \sigma^2_{I_mR_j} = \sigma^2_I$, one has

$$\begin{aligned}\Pr(|\mathscr{D}| = k) &= \prod_{R_i\in\mathscr{D}} \Pr\left(C^{\mathrm{RS}}_{S_bR_i} > R_s\right) \times \prod_{R_j\in\overline{\mathscr{D}}} \Pr\left(C^{\mathrm{RS}}_{S_bR_j} < R_s\right) \\ &= \left[\exp\left(-\frac{\theta}{\gamma_S\sigma^2_S}\right)\frac{\left(\sigma^2_S\right)^M}{\left(\sigma^2_S + \gamma_I\sigma^2_I\theta/\gamma_S\right)^M}\right]^k \\ &\quad\times\left[1 - \exp\left(-\frac{\theta}{\gamma_S\sigma^2_S}\right)\frac{\left(\sigma^2_S\right)^M}{\left(\sigma^2_S + \gamma_I\sigma^2_I\theta/\gamma_S\right)^M}\right]^{K-k},\end{aligned} \tag{35}$$

where $\theta = (2^{2R_s} - 1)$ and $\overline{\mathscr{D}}$ is the complementary set of the successful decoding set $\mathscr{D}$. By utilizing a similar way, the term $\Pr(\mathscr{D} = \emptyset)$ is calculated as

$$\begin{aligned}\Pr(\mathscr{D} = \emptyset) &= \prod_{R_k\in\mathbb{R}} \Pr\left(C^{\mathrm{RS}}_{S_bR_k} < R_s\right) \\ &= \left[1 - \exp\left(-\frac{\theta}{\gamma_S\sigma^2_S}\right)\frac{\left(\sigma^2_S\right)^M}{\left(\sigma^2_S + \gamma_I\sigma^2_I\theta/\gamma_S\right)^M}\right]^K.\end{aligned} \tag{36}$$

As discussed before, by utilizing a similar way as P_1, P_3 can be obtained as

$$\begin{aligned}P_3 = \sum_{n=0}^{N-1} C^n_{N-1}(-1)^n &\left[\frac{1 - \exp\left(-(n+1)\theta/\sigma^2_S\gamma_S\right)}{n+1}\right. \\ &+ \sum_{m_1=0}^{M-1}\exp\left(-\frac{(n+1)\theta}{\gamma_S\sigma^2_S}\right) \\ &\left.\times\frac{\gamma_I\sigma^2_I\theta}{\sigma^2_S\gamma_S\left((n+1)\gamma_I\sigma^2_I\theta/\sigma^2_S\gamma_S + 1\right)^{m_1+1}}\right].\end{aligned} \tag{37}$$

Similar to (20), the term P_4 is expressed as

$$\begin{aligned}P_4 = \int_0^\infty &\Pr\left(\max_{1\leqslant n\leqslant N, n\neq b}\left(\left|h_{S_nD}\right|^2\right) < x \mid x\right) \\ &\times\Pr\left(\max\left(\frac{\gamma_S x}{Y+1}, \frac{\gamma_S\left|h_{R_{\mathrm{best}}D}\right|^2}{Y+1}\right) < \theta \mid x\right) \\ &\times f_{|h_{S_bD}|^2}(x)\,dx.\end{aligned} \tag{38}$$

Proceeding as in Appendix B, P_4 can be obtained as

$$\begin{aligned}P_4 = \sum_{n=0}^{N-1}\sum_{k_1=0}^{|\mathscr{D}|} &C^n_{N-1}(-1)^n C^{k_1}_{|\mathscr{D}|}(-1)^{k_1}\exp\left(-\frac{k_1\theta}{\sigma^2_S\gamma_S}\right) \\ &\times\left[\frac{1 - \exp\left(-(n+1)\theta/\sigma^2_S\gamma_S\right)}{(n+1)\left(1 + k_1\theta\sigma^2_I\gamma_I/\sigma^2_S\gamma_S\right)^M}\right. \\ &+ \sum_{m_1=0}^{M-1}\exp\left(-\frac{(n+1)\theta}{\sigma^2_S\gamma_S}\right) \\ &\left.\cdot\frac{\gamma_I\sigma^2_I\theta\left(1 + k_1\theta\sigma^2_I\gamma_I/\sigma^2_S\gamma_S\right)^{m_1-M}}{\sigma^2_S\gamma_S\left(1 + k_1\gamma_I\sigma^2_I\theta/\sigma^2_S\gamma_S + (n+1)\gamma_I\sigma^2_I\theta/\sigma^2_S\gamma_S\right)^{m_1+1}}\right].\end{aligned} \tag{39}$$

On the other hand, similarly, according to (17) and using the theory of total probability, the IP of the RS strategy is formulated as

$$P^{\mathrm{RS}}_{\mathrm{int}} = \sum_{b=1}^{N}\sum_{k=0}^{K}\sum_{\mathscr{D}\subset\mathbb{R}}\Pr\left(|\mathscr{D}| = k,\ C^{\mathrm{RS}}_E > R_s\right). \tag{40}$$

During the two slots, note that E will intercept the message transmitted by both the selected best source S_b and the selected best relay $\mathsf{R}_{\mathrm{best}}$ and perform detection using both received signal copies. Thus, (40) can be rewritten as

$$P^{\mathrm{RS}}_{\mathrm{int}} = \sum_{b=1}^{N}\left[\Pr(\mathscr{D} = \emptyset)P_5 + \sum_{k=1}^{K}\sum_{\mathscr{D}\subset\mathbb{R}}\Pr(|\mathscr{D}| = k)P_6\right] \tag{41}$$

in which the terms P_5 and P_6 are, respectively, given by

$$P_5 = \Pr\left(\left|h_{S_bD}\right|^2 > \max_{1\leqslant n\leqslant N, n\neq b}\left(\left|h_{S_nD}\right|^2\right),\ C^{\mathrm{RS}}_{S_bE} > R_s\right), \tag{42}$$

$$P_6 = \Pr\left(\left|h_{S_bD}\right|^2 > \max_{1\leqslant n\leqslant N, n\neq b}\left(\left|h_{S_nD}\right|^2\right),\ C^{\mathrm{RS}}_E > R_s\right). \tag{43}$$

As discussed before, similar to P_2, P_5 can be obtained as

$$P_5 = \sum_{n=0}^{N-1}\frac{C^n_{N-1}(-1)^n\left(\sigma^2_E\right)^M}{(n+1)\left(\sigma^2_E + \gamma_I\sigma^2_I\theta/\gamma_S\right)^M}\exp\left(-\frac{\theta}{\gamma_S\sigma^2_E}\right). \tag{44}$$

Similar to (38), the term P_6 can be rewritten as

$$\begin{aligned}P_6 = \int_0^\infty &\Pr\left(\max_{1\leqslant n\leqslant N, n\neq b}\left(\left|h_{S_nD}\right|^2\right) < x \mid x\right) \\ &\times\Pr\left(\max\left(\frac{\gamma_S\left|h_{S_bE}\right|^2}{T+1}, \frac{\gamma_S\left|h_{R_{\mathrm{best}}E}\right|^2}{T+1}\right) > \theta \mid x\right) \\ &\times f_{|h_{S_bD}|^2}(x)\,dx.\end{aligned} \tag{45}$$

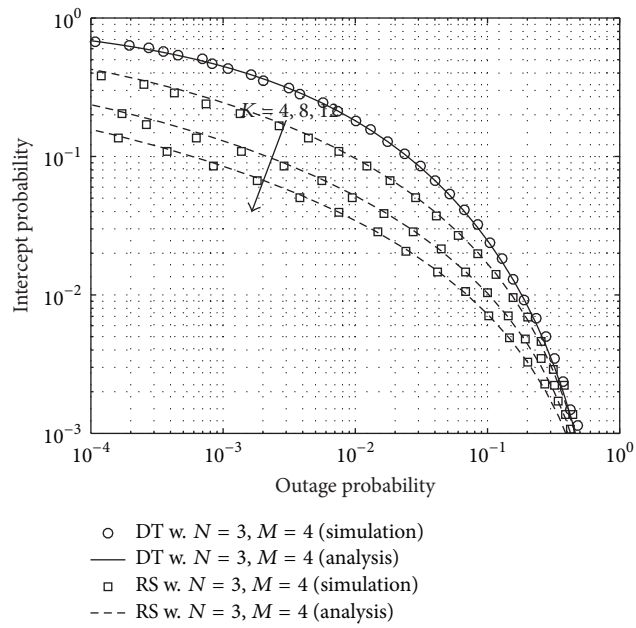

Figure 2: SRTs of the conventional DT strategy and RS strategy for different numbers of relays K with $\gamma_I = 15$ dB, $N = 3$, and $M = 4$.

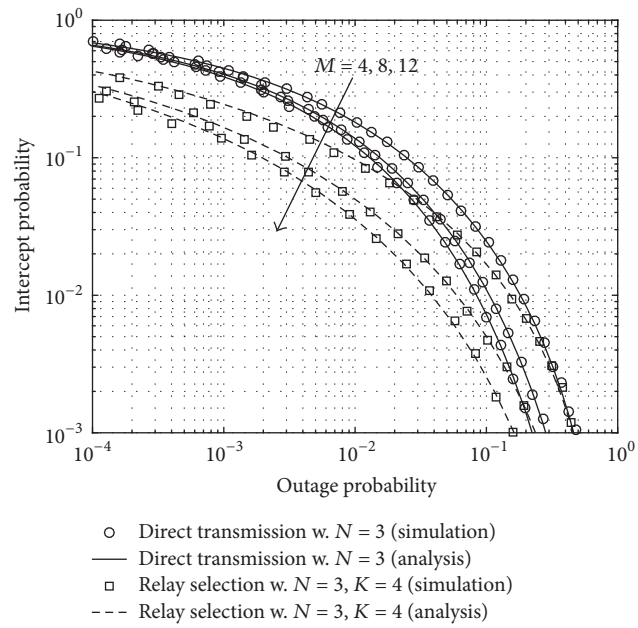

Figure 3: SRTs of the conventional DT strategy and RS strategy for different numbers of cochannel interferers M with $\gamma_I = 15$ dB, $N = 3$, and $K = 4$.

After some appropriate substitutions and via utilizing a similar derivation for P_4, P_6 can be obtained as

$$P_6 = \sum_{n=0}^{N-1} \frac{C_{N-1}^{n}(-1)^n}{(1+n)} \times \left[2\exp\left(-\frac{\theta}{\gamma_S \sigma_E^2}\right) \frac{\left(\sigma_E^2\right)^M}{\left(\sigma_E^2 + \gamma_I \sigma_I^2 \theta/\gamma_S\right)^M} - \exp\left(-\frac{2\theta}{\gamma_S \sigma_E^2}\right) \frac{\left(\sigma_E^2 \sigma_E^2\right)^{2M}}{\left(\sigma_E^2 + \gamma_I \sigma_I^2 \theta/\gamma_S\right)^{2M}} \right]. \quad (46)$$

Therefore, after some incorporations and iterations, the closed-form outage probability and intercept probability expressions of both the DT and RS schemes with multiple cochannel interferers can be achieved.

4. Simulation Evaluations

In this section, the SRT performances of the DT and RS schemes are evaluated by simulations. The simulation parameters are set as follows: $R_s = 1$ bit/s/Hz, $\sigma^2_{S_bD} = \sigma^2_{S_bR_k} = \sigma^2_{R_kD} = \sigma^2_S = 1$, $\sigma^2_{I_mR_k} = \sigma^2_{I_mD} = \sigma^2_{I_mE} = \sigma^2_I = 0.1$, and $\sigma^2_{S_bE} = \sigma^2_{R_{\text{best}}E} = \sigma^2_E = 0.2$.

Figures 2–4 show the curves of the theoretical SRT analysis. As can be seen from the figures the intercept probability is presented as a function of the outage probability. Obviously, it can be seen that the simulation results match well with the theoretical analysis. Figure 2 shows the intercept probabilities versus the outage probabilities of the conventional DT strategy as well as the RS strategy at

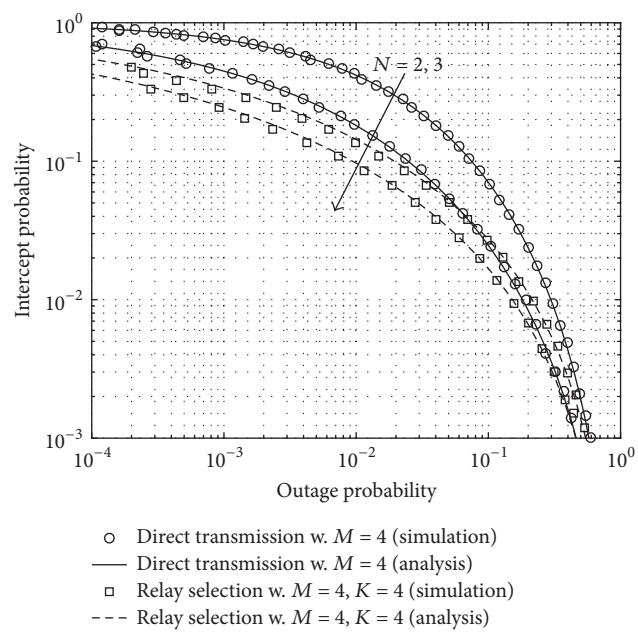

Figure 4: SRTs of the conventional DT strategy and RS strategy for different numbers of sources N with $\gamma_I = 15$ dB, $M = 4$, and $K = 4$.

different K ($K = \{4, 8, 12\}$). Figure 2 also shows that as the outage probabilities increase, the intercept probabilities of the conventional DT and the RS schemes decrease. This confirms that there exists a tradeoff between the intercept probability and the outage probability. Another phenomenon can be observed in Figure 2; that is, the SRT of the RS strategy always outperforms that of the conventional DT strategy. Moreover, the SRT of the RS strategy is also improved with increasing K

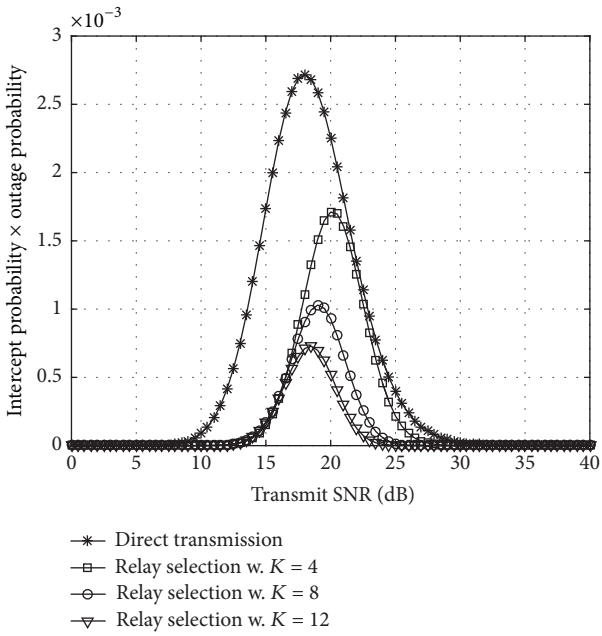

Figure 5: IP × OP versus the transmit SNR γ_S of the conventional DT strategy and RS strategy for different numbers of relays K with $\gamma_I = 15$ dB, $N = 3$, and $M = 4$.

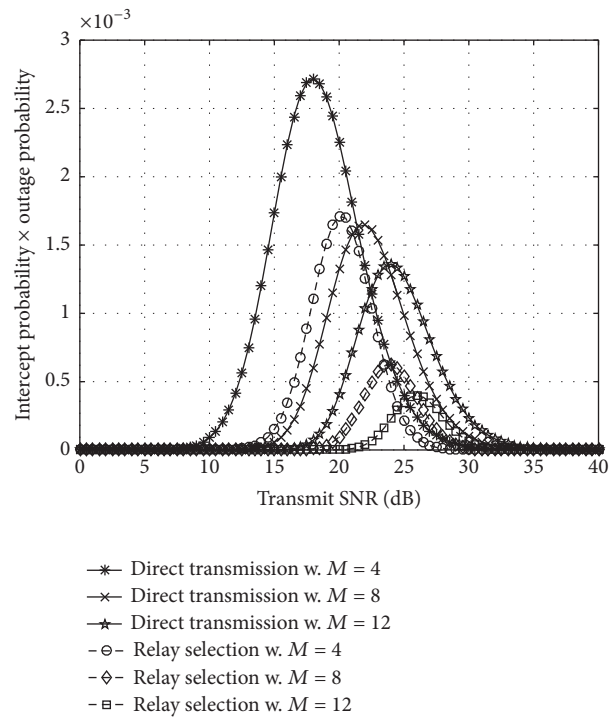

Figure 6: IP × OP versus the transmit SNR γ_S of the conventional DT strategy and RS strategy for different numbers of cochannel interferers M with $\gamma_I = 15$ dB, $N = 3$, and $K = 4$.

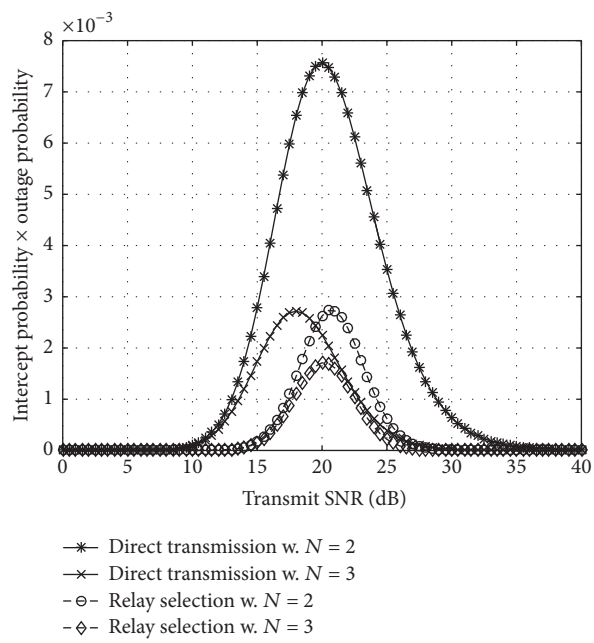

Figure 7: IP × OP versus the transmit SNR γ_S of the conventional DT strategy and RS strategy for different numbers of sources N with $\gamma_I = 15$ dB, $M = 4$, and $K = 4$.

(from 4 to 12). This is due to the reason that the diversity gain can be obtained with the increase of the number of relays.

Figure 3 depicts the intercept probabilities versus the outage probabilities of the conventional DT strategy as well as the RS strategy at different M ($M = \{4, 8, 12\}$). Figure 3 also shows that when the outage probabilities change from 10^{-4} to 10^{0}, the intercept probabilities of the conventional DT and the RS schemes decrease correspondingly. Moreover, for a given M, the SRT of the RS strategy performs better than that of the conventional DT strategy. It is also seen that the SRTs of the conventional DT and the RS schemes are also improved with increasing M (from 4 to 12).

Figure 4 shows the intercept probabilities versus the outage probabilities of the conventional DT strategy as well as the RS strategy at different N ($N = \{2, 3\}$). Similar to Figure 3, the intercept probabilities of the conventional DT and the RS schemes decrease correspondingly, as the outage probabilities increase from 10^{-4} to 10^{0}. Moreover, for a given N, the SRT of the RS strategy always outperforms that of the conventional DT strategy. The SRTs of the conventional DT and the RS schemes are also improved with increasing N (from 2 to 3). By jointly considering Figures 2–4, it is found that as the outage probabilities increase, the intercept probabilities of the conventional DT and the RS schemes decrease, implying that the SRT indeed exists between the intercept probability and the outage probability. Meanwhile, the improvement of the SRT is obtained with increasing the number of sources, relays, and cochannel interferers. Moreover, it is also shown that the SRT of the RS strategy consistently outperforms that of the conventional DT strategy.

In order to further evaluate the SRT, the products of the intercept probabilities and the outage probabilities of the conventional DT strategy as well as the RS strategy are plotted in Figures 5–7. Figure 5 shows the (IP × OP) products of the conventional DT strategy as well as the RS strategy against the transmit SNR γ_S at different numbers of available relays K ($K = \{4, 8, 12\}$). Figure 5 also shows that there exists an (IP × OP) peak with the increase of the transmit SNR γ_S. This is due to the reason that the IP in the low SNR regime comes close to 0, and the OP in the high SNR

regime comes close to 0. Particularly, the presence of the (IP× OP) peak is another perspective that the SRT indeed exists between the intercept probability and the outage probability. Clearly, it is also seen from Figure 5 that the maximum (IP × OP) product of the RS strategy is smaller than that of the conventional DT strategy, which means the RS strategy is always better than the conventional DT strategy in terms of the (IP × OP) product. Moreover, the maximum (IP × OP) product decreases significantly with increasing K (from 4 to 12). It implies the SRT of the RS strategy is improved accordingly.

Figure 6 shows the (IP×OP) products of the conventional DT strategy as well as the RS strategy against the transmit SNR γ_S at different M ($M = \{4, 8, 12\}$). Similar to Figure 5, there also exists an (IP × OP) peak with the increase of the transmit SNR γ_S. Figure 6 also shows that, for a given M, the RS strategy outperforms the DT strategy in terms of the (IP × OP) product. Moreover, the SRTs of the conventional DT and the RS schemes are also improved with increasing M (from 4 to 12).

Figure 7 shows the (IP×OP) products of the conventional DT strategy as well as the RS strategy versus the transmit SNR γ_S at different N ($N = \{2, 3\}$). Similar to Figure 5, there also exists an (IP × OP) peak with the increase of the transmit SNR γ_S. Meanwhile, for a given N, the RS strategy outperforms the conventional DT strategy in terms of the (IP×OP) product, and when the number of sources increases from $N = 2$ to $N = 3$, the maximum (IP × OP) product can be minimized so that the SRTs of the conventional DT and the RS schemes are improved. By jointly considering Figures 5–7, the improvement of the SRT performance in terms of the (IP × OP) product can be achieved by increasing the number of relays, sources, and cochannel interferers. Moreover, it is also shown that the SRT performance of the RS strategy is better than that of the conventional DT strategy in terms of the product of the IP and the OP.

5. Conclusions

In this paper, we presented the PLS of a multisource multirelay cooperative communication network by considering the influence of cochannel interference from an SRT perspective. Under impact of cochannel interferers, we adopted an SINR-based method to analyze the SRT performance characterized by the OP and the IP. We derived the closed-form IP and OP expressions of both the conventional DT strategy and RS strategy over Rayleigh fading channels, respectively. We showed that when the OP (reliability) requirement is relaxed, the IP (security) performance improves and vice versa. It confirms that there is an SRT existing between the OP and the IP. We also showed that a better SRT performance can be achieved by increasing the number of sources, relays, and cochannel interferers. In addition, the RS strategy generally outperforms the conventional DT strategy in terms of the product of the OP and the IP.

Appendix

A. Derivation of (24)

According to (23), P_1 is rewritten as

$$\begin{aligned} P_1 &= \sum_{n=0}^{N-1} \frac{C_{N-1}^n (-1)^n}{\sigma_{S_bD}^2} \int_0^{\Delta/\gamma_S} \exp\left(-\frac{nx}{\sigma_{S_nD}^2} - \frac{x}{\sigma_{S_bD}^2}\right) dx \\ &\quad + \sum_{n=0}^{N-1} \sum_{m_1=0}^{M-1} \frac{C_{N-1}^n (-1)^n}{m_1! \sigma_{S_bD}^2} \exp\left(\frac{1}{\gamma_I \sigma_{I_mD}^2}\right) \\ &\quad \times \int_{\Delta/\gamma_S}^{\infty} \exp\left(-\left(\frac{n}{\sigma_{S_nD}^2} + \frac{1}{\sigma_{S_bD}^2} + \frac{\gamma_S}{\gamma_I \sigma_{I_mD}^2 \Delta}\right) x\right) \\ &\quad \times \left(\frac{\gamma_S x}{\gamma_I \sigma_{I_mD}^2 \Delta} - \frac{1}{\gamma_I \sigma_{I_mD}^2}\right)^{m_1} dx. \end{aligned} \tag{A.1}$$

After some incorporations and necessary mathematical manipulations, P_1 can be calculated as

$$\begin{aligned} P_1 &= \sum_{n=0}^{N-1} \frac{C_{N-1}^n (-1)^n}{n\sigma_{S_bD}^2/\sigma_{S_nD}^2 + 1} \\ &\quad \cdot \left[1 - \exp\left(-\frac{\left(n\sigma_{S_bD}^2/\sigma_{S_nD}^2 + 1\right)\Delta}{\sigma_{S_bD}^2 \gamma_S}\right)\right] \\ &\quad + \sum_{n=0}^{N-1} \sum_{m_1=0}^{M-1} \frac{C_{N-1}^n (-1)^n}{m_1! \sigma_{S_bD}^2} \exp\left(\frac{1}{\gamma_I \sigma_{I_mD}^2}\right) \\ &\quad \times \exp\left(-\frac{\left(n/\sigma_{S_nD}^2 + 1/\sigma_{S_bD}^2 + \gamma_S/\gamma_I \sigma_{I_mD}^2 \Delta\right)\left(1/\gamma_I \sigma_{I_mD}^2\right)}{\gamma_S/\gamma_I \sigma_{I_mD}^2 \Delta}\right) \\ &\quad \times \frac{\left(\gamma_S/\gamma_I \sigma_{ID}^2 \Delta\right)^{m_1}}{\left(n/\sigma_{S_nD}^2 + 1/\sigma_{S_bD}^2 + \gamma_S/\gamma_I \sigma_{I_mD}^2 \Delta\right)^{m_1+1}} \Gamma(m_1 + 1, 0). \end{aligned} \tag{A.2}$$

For notational convenience, considering $\sigma_{S_bD}^2 = \sigma_{S_nD}^2 = \sigma_S^2$ and $\sigma_{I_mD}^2 = \sigma_I^2$ and using the equation $\Gamma(n, x) = (n-1)!\exp(-x)\sum_{m=0}^{n-1}(x^m/m!)$ [32], P_1 can be achieved as shown in (24).

This completes the derivation of (24).

B. Derivation of (39)

According to (38), the second term can be expressed as

$$\begin{aligned} &\Pr\left(\max\left(\frac{\gamma_S x}{Y+1}, \frac{\gamma_S \left|h_{R_{\text{best}}D}\right|^2}{Y+1}\right) < \theta \mid x\right) \\ &= \begin{cases} \underbrace{\int_0^{\infty} \Pr\left(\frac{\gamma_S \left|h_{R_{\text{best}}D}\right|^2}{y+1} < \theta \mid x\right) f_Y(y)\, dy}_{A_1} & x < \frac{\theta}{\gamma_S} \\ \underbrace{\int_{\gamma_S x/\theta - 1}^{\infty} \Pr\left(\frac{\gamma_S \left|h_{R_{\text{best}}D}\right|^2}{y+1} < \theta \mid x\right) f_Y(y)\, dy}_{A_2} & x > \frac{\theta}{\gamma_S}, \end{cases} \end{aligned} \tag{B.1}$$

where the term $\Pr(\gamma_S|h_{R_{\text{best}}D}|^2/(y+1) < \theta \mid x)$ can be calculated as

$$\begin{aligned}\Pr\left(\frac{\gamma_S\left|h_{R_{\text{best}}D}\right|^2}{y+1} < \theta \mid x\right) &= \Pr\left(\max_{R_k\in\mathscr{D}}\left(\left|h_{R_kD}\right|^2\right) < \frac{\theta(y+1)}{\gamma_S} \mid x\right) \\ &= \prod_{R_k\in\mathscr{D}}\Pr\left(\left|h_{R_kD}\right|^2 < \frac{\theta(y+1)}{\gamma_S} \mid x\right) \\ &= \sum_{k_1=0}^{|\mathscr{D}|} C_{|\mathscr{D}|}^{k_1}(-1)^{k_1}\exp\left(-\frac{k_1\theta(y+1)}{\sigma_{R_{k_1}D}^2\gamma_S}\right).\end{aligned} \tag{B.2}$$

Substituting (B.2) into (B.1), one has

$$\begin{aligned}A_1 &= \sum_{k_1=0}^{|\mathscr{D}|} C_{|\mathscr{D}|}^{k_1}(-1)^{k_1}\exp\left(-\frac{k_1\theta}{\sigma_{R_{k_1}D}^2\gamma_S}\right) \\ &\quad\times\int_0^\infty \exp\left(-\frac{k_1\theta y}{\sigma_{R_{k_1}D}^2\gamma_S}\right)f_Y(y)\,dy.\end{aligned} \tag{B.3}$$

Using the equation $\int_0^\infty x^m\exp(-\beta x^n)dx = \Gamma((m+1)/n)/n\beta^{(m+1)/n}$ [32], A_1 can be calculated as

$$\begin{aligned}A_1 &= \sum_{k_1=0}^{|\mathscr{D}|} C_{|\mathscr{D}|}^{k_1}(-1)^{k_1}\exp\left(-\frac{k_1\theta}{\sigma_{R_{k_1}D}^2\gamma_S}\right) \\ &\quad\cdot\frac{1}{\left(1+k_1\theta\sigma_{I_mD}^2\gamma_I/\sigma_{R_{k_1}D}^2\gamma_S\right)^M}.\end{aligned} \tag{B.4}$$

By utilizing a similar way, A_2 can be obtained as

$$\begin{aligned}A_2 &= \sum_{k_1=0}^{|\mathscr{D}|}\sum_{m_1=0}^{M-1}\frac{C_{|\mathscr{D}|}^{k_1}(-1)^{k_1}}{m_1!} \\ &\quad\cdot\exp\left(-\left(\frac{k_1}{\sigma_{R_{k_1}D}^2}+\frac{\gamma_S}{\gamma_I\sigma_{I_mD}^2\theta}\right)x\right) \\ &\quad\times\exp\left(\frac{1}{\gamma_I\sigma_{I_mD}^2}\right) \\ &\quad\cdot\frac{\left(\gamma_Sx/\gamma_I\sigma_{I_mD}^2\theta-1/\gamma_I\sigma_{I_mD}^2\right)^{m_1}}{\left(1+k_1\theta\sigma_{I_mD}^2\gamma_I/\sigma_{R_{k_1}D}^2\gamma_S\right)^{M-m_1}}.\end{aligned} \tag{B.5}$$

Substituting (21) and (B.1) into (38), P_4 can be expressed as

$$\begin{aligned}P_4 &= \underbrace{\int_0^{\theta/\gamma_S}\sum_{n=0}^{N-1}C_{N-1}^n(-1)^n\exp\left(-\frac{nx}{\sigma_{S_nD}^2}\right)A_1f_{|h_{S_bD}|^2}(x)\,dx}_{B_1} \\ &\quad+\underbrace{\int_{\theta/\gamma_S}^\infty\sum_{n=0}^{N-1}C_{N-1}^n(-1)^n\exp\left(-\frac{nx}{\sigma_{S_nD}^2}\right)A_2f_{|h_{S_bD}|^2}(x)\,dx}_{B_2}.\end{aligned} \tag{B.6}$$

Then, incorporating (B.4) into (B.6) and employing some mathematical manipulations, B_1 can be calculated as

$$\begin{aligned}B_1 &= \sum_{n=0}^{N-1}\sum_{k_1=0}^{|\mathscr{D}|}C_{N-1}^n(-1)^nC_{|\mathscr{D}|}^{k_1}(-1)^{k_1} \\ &\quad\cdot\frac{\exp\left(-k_1\theta/\sigma_{R_{k_1}D}^2\gamma_S\right)}{\left(1+k_1\theta\sigma_{I_mD}^2\gamma_I/\sigma_{R_{k_1}D}^2\gamma_S\right)^M}\times\frac{1}{\sigma_{S_bD}^2} \\ &\quad\cdot\int_0^{\theta/\gamma_S}\exp\left(-\frac{nx}{\sigma_{S_nD}^2}-\frac{x}{\sigma_{S_bD}^2}\right)dx \\ &= \sum_{n=0}^{N-1}\sum_{k_1=0}^{|\mathscr{D}|}\frac{C_{N-1}^n(-1)^nC_{|\mathscr{D}|}^{k_1}(-1)^{k_1}}{n\sigma_{S_bD}^2/\sigma_{S_nD}^2}\exp\left(-\frac{k_1\theta}{\sigma_{R_{k_1}D}^2\gamma_S}\right) \\ &\quad\times\frac{1-\exp\left(-\left(n\sigma_{S_bD}^2/\sigma_{S_nD}^2+1\right)\theta/\sigma_{S_bD}^2\gamma_S\right)}{\left(1+k_1\theta\sigma_{I_mD}^2\gamma_I/\sigma_{R_{k_1}D}^2\gamma_S\right)^M}.\end{aligned} \tag{B.7}$$

By utilizing a similar way, B_2 can be obtained as

$$\begin{aligned}B_2 &= \sum_{n=0}^{N-1}\sum_{k_1=0}^{|\mathscr{D}|}\sum_{m_1=0}^{M-1}\frac{C_{N-1}^n(-1)^nC_{|\mathscr{D}|}^{k_1}(-1)^{k_1}\gamma_I\sigma_{I_mD}^2\theta}{\sigma_{S_bD}^2\gamma_S}\times\exp\left(-\frac{k_1\theta}{\sigma_{R_{k_1}D}^2\gamma_S}\right)\exp\left(-\frac{\left(n\sigma_{S_bD}^2/\sigma_{S_nD}^2+1\right)\theta}{\sigma_{S_bD}^2\gamma_S}\right) \\ &\quad\times\frac{\left(1+k_1\theta\sigma_{I_mD}^2\gamma_I/\sigma_{R_{k_1}D}^2\gamma_S\right)^{m_1-M}}{\left(1+k_1\gamma_I\sigma_{I_mD}^2\theta/\sigma_{R_{k_1}D}^2\gamma_S+\left(n\sigma_{S_bD}^2/\sigma_{S_nD}^2+1\right)\gamma_I\sigma_{I_mD}^2\theta/\sigma_{S_bD}^2\gamma_S\right)^{m_1+1}}.\end{aligned} \tag{B.8}$$

Incorporating (B.7) and (B.8) into (B.6), and for simplicity, considering $\sigma^2_{S_bD} = \sigma^2_{S_nD} = \sigma^2_S$ and $\sigma^2_{I_mD} = \sigma^2_I$, P_4 can be obtained as shown in (39).

This completes the derivation of (39).

Data Availability

The underlying data comes from simulation results.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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