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Research Article

Distributed Antenna-and-Relay Selection Schemes for MIMO Cooperative Relay Network

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Relay selection, antenna selection, and link selection are three potent means to enrich network capacity in MIMO relaying networks. To reduce feedback overhead, in this paper, three distributed antenna-and-relay selection schemes are proposed for AF multiple-relay network, which is equipped with multiple antennas at nodes. Closed-form formulations of system outage probability are derived for these schemes, as well as the lower bounds and upper bounds. Furthermore, the approximate expressions of outage probability at high SNR regime are also derived, showing that the proposed optimal strategy can achieve full diversity order. In addition, link selection scheme can improve spectral efficiency since it saves one time slot when direct link is selected.

1. Introduction

The combined application of cooperative communications and multiple-input multiple-output (MIMO) techniques has attracted much attention in wireless networks [1–3]. It proves to be an effective means to increase system capacity and link reliability. However, these techniques increase the system size, complexity, and cost. Therefore, transmit antenna selection (TAS) methods are proposed at the transmitter side which also can achieve full cooperative diversity with lower complexity of implementation [4, 5]. At the receiver side, some diversity-combining techniques are used, such as maximal-ratio combining (MAC) and selection-combining (SC) [4].

In [6], the SER (symbol error rate) in a MIMO cooperative system which equipped an amplify-and-forward (AF) relay based on TAS/MAC was investigated. Furthermore, in [7], performance comparison between optimal TAS/MAC and TAS/SC strategies was performed in a multirelay MIMO system. Similar comparison was made in [8], which investigated a MIMO decode-and-forward (DF) relaying network. Moreover, authors analysed system outage of the optimal relay and antenna selection strategy in MIMO DF relaying system under Nakagami-m fading conditions in [9]. It is noteworthy that all the authors in [6–9] took no account of the direct link between source and destination. Various TAS strategies were proposed in [10–16] by considering direct path in the system. In [10], both optimal and suboptimal TAS/MAC strategies were proposed in cooperative system which can achieve full diversity. However, the implementation complexity was considerable. To overcome this, in [11], a suboptimal TAS/MAC scheme, namely, DAS was presented, which only needs a low delay/feedback overhead. In [12], two low-cost strategies (DAS/SC and DAS/LS) were proposed for relaying networks based on [11] which achieve full diversity order and nearly-full diversity order, respectively. In [13], similar schemes were proposed in a multiantenna relay system. Furthermore, in [14], one diversity-optimal and three suboptimal TAS/SC strategies were proposed in a multirelay network, which equipped with multiple antennas both at source and the destination and only one antenna at relay. The implementation complexity of three suboptimal schemes is simpler than the diversity-optimal scheme at the cost of reduced performance. In [15, 16], the performance of an optimal TAS/MAC strategy in MIMO AF relaying system is analysed, where the transmitting antennas in source and relay are selected through the CSI estimates for all links to maximize the SNR received by the destination. Moreover, the distributed algorithms are potent methods in many communication scenarios [17, 18]. Most of the relay and antenna selection schemes in the literature need to estimate the CSI of all links, calculate the signal-to-noise ratio of each possible path at the destination, and require high complexity calculation at each node. In order to reduce implementation complexity, we proposed three distributed relay and antenna selection schemes in a MIMO AF relaying network. Exact formulations of the outage probability are derived as well as upper bounds and lower bounds for all three schemes. And asymptotic expressions at high SNR are also derived for the obtained bounds to evaluate the diversity orders of proposed schemes. Finally, comparisons of all proposed schemes are performed through simulations in terms of spectral efficiency and outage probability.

2. System Model

A MIMO AF relaying network is considered in this paper which compose by a source S with N_s antennas, a destination D with N_d antennas and M relays with N_r antennas, as shown in Figure 1. The direct link between S and D is available, and all nodes in this model are working in the half-duplex mode. The information received in D through the direct $(S_i \longrightarrow D_j)$ and relayed $(S_i \longrightarrow R_{q,l} \longrightarrow D_j)$ links are combined by means of SC, where $i \in \{1, 2, \cdots, N_s\}$, $p, q \in \{1, 2, \cdots, N_r\} p, q \in \{1, 2, \cdots, N_r\}$, $j, \in \{1, 2, \cdots, N_d\}$, and $l \in \{1, 2, \cdots, M\}$.

The transmit antenna and relay selection are executed at S and R before communication process, according to the procedure described in the next section. Then, the traditional two-phase amplify-and-forward cooperative transmission takes place as followed in [16]. Therefore, the end-to-end SNR is

$$\gamma^{i,l,q} = \max\left(\gamma_{S_i D_{j1}}, \frac{\gamma_{S_i R_{p,l}} \gamma_{R_{q,l} D_{j2}}}{\gamma_{S_i R_{p,l}} + \gamma_{R_{q,l} D_{j2}} + 1}\right), \quad (1)$$

where $\gamma_{S_i D_{j1}} \triangleq (P_S/N_0)|h_{S_i, D_{j1}}|^2$, $\gamma_{S_i R_{p,l}} \triangleq (P_S/N_0)|h_{S_i, R_{p,l}}|^2$, and $\gamma_{R_{q,l} D_{j2}} \triangleq (P_R/N_0)|h_{R_{q,l}, D_{j2}}|^2$.

Herein, P_S and P_R are, respectively, transmit powers in source and relays. h_{S_i, D_j}, $h_{S_i, R_{p,l}}$, and $h_{R_{q,l}, D_j}$ denote the channel coefficients between the ith antenna to the jth one in $S \longrightarrow D$ hop, between the ith antenna to the pth one in the $S \longrightarrow R_l$ hop, and the qth antenna to the jth antenna in the $R_l \longrightarrow D$ hop, respectively. N_0 is noise variance of additive white Gaussian noises (AWGNs). As in [19], the amplifying factor at R is $G \triangleq \sqrt{P_S/(P_S E[|h_{S_i R_{p,l}}|^2] + N_0)}$. We assume $\bar{\gamma}_{SD} \triangleq E[\gamma_{S_i D_{j1}}]$, $\bar{\gamma}_{SR_l} \triangleq E[\gamma_{S_i R_{p,l}}]$, $\bar{\gamma}_{R_l D} \triangleq E[\gamma_{R_{q,l} D_{j2}}]$, $\forall i = 1, \cdots, N_s$, $\forall p = \forall q = 1, \cdots, N_r$, and $\forall j1 = \forall j2 = 1, \cdots, N_d$.

For convenience, some expressions used in this article are listed as

$$\begin{cases} \lambda_{SR_l} = \max_{1 \le i \le N_s, 1 \le p \le N_r}\left[\gamma_{S_i R_{p,l}}\right], \\ \lambda_{S_{i*} R_l} = \max_{1 \le p \le N_r}\left[\gamma_{S_{i*} R_{p,l}}\right], \\ \lambda_{R_l D} = \max_{1 \le q \le N_r, 1 \le j \le N_d}\left[\gamma_{R_{q,l} D_j}\right], \\ \lambda_{SD} = \max_{1 \le i \le N_s, 1 \le j \le N_d}\left[\gamma_{S_i D_j}\right], \\ \lambda_l = \min\left(\lambda_{SR_l}, \lambda_{R_l D}\right). \end{cases} \quad (2)$$

The SNR in all links follow an exponential distribution, Therefore, the CDF of λ_{SR_l} is

$$\begin{aligned} F_{\lambda_{SR_l}}(t) &= \Pr\left\{\lambda_{SR_l} < t\right\} = \Pr\left\{\max_{1 \le i \le N_s, 1 \le p \le N_r}\left[\gamma_{S_i R_{p,l}}\right] < t\right\} \\ &= \left[1 - \exp\left(-\frac{t}{\bar{\gamma}_{SR_l}}\right)\right]^{N_s N_r}. \end{aligned} \quad (3)$$

Similarly [20], the CDF of $\lambda_{S_{i*} R_l}$, $\lambda_{R_l D}$, and λ_{SD} can be, respectively, obtained by $F_{\lambda_{S_{i*} R_l}}(t) = [1 - \exp(-t/\bar{\gamma}_{SR_l})]^{N_r}$, $F_{\lambda_{R_l D}}(t) = [1 - \exp(-t/\bar{\gamma}_{R_l D})]^{N_r N_d}$, and $F_{\lambda_{SD}}(t) = [1 - \exp(-t/\bar{\gamma}_{SD})]^{N_s N_d}$.

Therefore, the PDF of λ_{SR_l}, $\lambda_{R_l D}$, and λ_{SD} can be, respectively, expressed by

$$f_{\lambda_{SR_l}}(t) = \frac{dF_{\lambda_{SR_l}}(t)}{dt} = \frac{N_s N_r \exp\left(-t/\bar{\gamma}_{SR_l}\right)}{\bar{\gamma}_{SR_l}}\left[1 - \exp\left(-\frac{t}{\bar{\gamma}_{SR_l}}\right)\right]^{N_s N_r - 1}, \quad (4)$$

$$f_{\lambda_{SD}}(t) = \frac{N_s N_d \exp(-t/\bar{\gamma}_{SD})}{\bar{\gamma}_{SD}}\left[1 - \exp\left(-\frac{t}{\bar{\gamma}_{SD}}\right)\right]^{N_s N_d - 1}, \quad (5)$$

$$f_{\lambda_{R_l D}}(t) = \frac{N_r N_d \exp\left(-t/\bar{\gamma}_{R_l D}\right)}{\bar{\gamma}_{R_l D}}\left[1 - \exp\left(-\frac{t}{\bar{\gamma}_{R_l D}}\right)\right]^{N_r N_d - 1}. \quad (6)$$

3. Antenna and Relay Selection Scheme

Optimal relay and transmitting antenna selection criterion [16] needs a large amount of feedback overhead and also considerable computation complexity in destination. Therefore, we propose three schemes to accomplish the relay and transmitting antenna selection by lower complexity and less feedback overhead. Moreover, the diversity-combining technique used in our work is SC which can also reduce the system complexity.

3.1. DAS/SC Optimal Scheme. The following is the steps involved in antenna and relay selection.

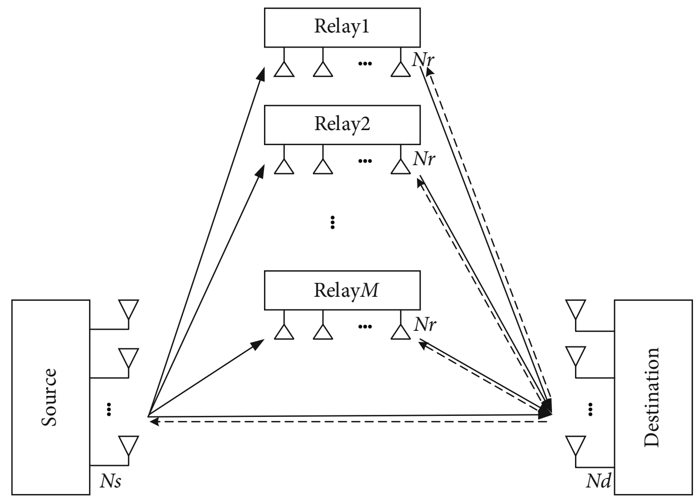

Figure 1: MIMO AF relaying network.

(i) *Step 1*. D from each antenna broadcasts 1-bit reverse pilot signal [13], thus, all relays and source can estimate instantaneous SNR value toward to D. Therefore, the best transmit antenna of l-th relay can be selected

$$\{q_l\} = \arg\ \max_{1\le q\le N_r, 1\le j\le N_d}\left[\gamma_{R_{q,l}D_j}\right]. \tag{7}$$

(ii) *Step 2*. The i -th source antenna broadcasts a pilot signal, and R and D receive this signal by means of SC

(iii) *Step 3*. Each relay amplifies and forwards the receive signal through the respective selected transmitting antenna in turn. D receives them by the means of SC and selects the best relay based on the following decision rule

$$\{l_i\} = \arg\ \max_{1\le l\le M, 1\le j\le N_d}\left[\frac{\gamma_{S_iR_{p_l l}}\gamma_{R_{q_l,l}D_{j2}}}{\gamma_{S_iR_{p_l,l}} + \gamma_{R_{q_l,l}D_{j2}} + 1}\right]. \tag{8}$$

Moreover, D combines signal from the best relay and the signal from Step 2 by the means of SC. Therefore, SNR of the system where signal delivered from the ith source antenna is

$$\gamma^{i,l_i,q_{l_i}} = \max\left\{\gamma_{S_iD_{j_1}}, \frac{\gamma_{S_iR_{p_l l_i}}\gamma_{R_{q_l,l_i}D_{j2}}}{\gamma_{S_iR_{p_l,l_i}} + \gamma_{R_{q_l,l_i}D_{j2}} + 1}\right\}. \tag{9}$$

(iv) *Step 4*. Let $i = i + 1$, make $i = N_s$ by repeating Steps 2 and 3. Then, the best transmit antenna of source in this system is

$$\{i*, j*, q*\} = \arg\ \max_i\left[\gamma^{i,l_i,q_{l_i}}\right], \tag{10}$$

where $i*$, $l*$, and $q*$ are the selected source transmitting antenna, the selected relay, and the relay transmitting antenna, respectively.

(v) *Step 5*. Source start communication process, where the $i*$th source antenna deliver signals to destination with the aid of the $l*$th relay. Here, D combines signal from S in first slot and signal from R in second slot using selective combining. End-to-end SNR of this system is

$$\gamma^{i*,l*,q*} = \max_i\left[\gamma^{i,l*,q*}\right]. \tag{11}$$

3.2. DAS/SC Suboptimal Scheme. The DAS/SC suboptimal strategy is presented to reduce signal overhead. The selection of source transmitting antenna relies solely on the direct link. The following is the steps involved in this scheme.

(i) *Step 1*. The same with Step 1 in DAS/SC optimal scheme. The best transmit antenna of source are selected based on the following decision rule

$$\{i*\} = \arg\ \max_{1\le i\le N_r, 1\le j\le N_d}\left[\gamma_{S_iD_j}\right]. \tag{12}$$

SNR from S to D is

$$\gamma_{S_{i*}D_{j1}} = \max_{1\le i\le N_r, 1\le j\le N_d}\left[\gamma_{S_iD_j}\right]. \tag{13}$$

(ii) *Step 2*. The $i*$th source antenna broadcasts a pilot signal, and R receives this signal by means of SC. Then, each relay estimate SNR of the relayed ($S_i \longrightarrow R_{q,l} \longrightarrow D_j$) link using

$$\gamma_{S_{i*}R_{p_l,l,q_l}D_j} = \frac{\gamma_{S_{i*}R_{p_l,l}}\gamma_{R_{q_l,l}D_j}}{\gamma_{S_{i*}R_{p_l,l}} + \gamma_{R_{q_l,l}D_j} + 1}. \quad (14)$$

Afterward, each relay node starts a timer according to its own estimate SNR. Similar to [21], the initial value T_l of this timer is inversely proportional to the relayed link SNR $\gamma_{S_{i*}R_{p_l,l,q_l}D_j}$, according to the following equation:

$$T_l = \left\lfloor \frac{\alpha}{\gamma_{S_{i*}R_{p_l,l,q_l}D_j}} \right\rfloor. \quad (15)$$

Here, α is a constant value.

(iii) *Step 3*. The "best" relay gets expired first. The relay selection can be expressed as (16). And it broadcasts feedback information. Other relays stop their timer as soon as receiving this information. Meanwhile, source starts its communication process, where the $i*$ th source antenna transmits signal to destination with the aid of the $l*$ th relay

$$\{l*\} = \arg\min\,[T_l]. \quad (16)$$

(iv) *Step 4*. Source start communication process. The end-to-end SNR in the network is

$$\gamma^{i*,l*,q*} = \max\left\{\gamma_{S_{i*}D_{j1}}, \gamma_{S_{i*}R_{p_{l*},l*,q_{l*}}D_{j2}}\right\}. \quad (17)$$

3.3. DAS/LS Scheme. The DAS/LS is proposed to improve the spectral efficiency. And the following are the steps contained in DAS/LS scheme for choosing relay and transmitting antenna.

(i) *Step 1*. The same with Step 1 in DAS/SC suboptimal scheme. The SNR from S to D is expressed in (13). If $\gamma_{S_{i*}D_{j1}} > 2^{R_0} - 1$, where R_0 is system transmission rate. S broadcasts feedback information to all R and D. And source starts communication process, where the $i*$ th source antenna delivers signal to destination only through the direct link

(ii) *Step 2*. If $\gamma_{S_{i*}D_{j1}} < 2^{R_0} - 1$, the $i*$ th source antenna broadcasts a pilot signal, and R receives this signal by means of SC. Then, each antenna estimates SNR of the relayed ($S_{i*} \longrightarrow R_l \longrightarrow D_j$) link just like Step 2 and Step 3 in DAS/SC suboptimal scheme

(iii) *Step 3*. The transmitting antenna of source starts its communication process only through the relayed ($S_{i*} \longrightarrow R_{l*} \longrightarrow D_j$) link

4. Performance Analysis

The outage probability of the proposed schemes is obtained in this chapter. And asymptotic analysis is executed, as well as the diversity order.

4.1. DAS/SC Optimal Scheme. Outage probability is mathematically formulated as

$$\begin{aligned} P_{\text{out}}^{\text{opt-sc}} &= \Pr\left\{\frac{1}{2}\log\left(1+\gamma^{i*,l*,q*}\right) < R_0\right\} \\ &= \Pr\left\{\max\left[\gamma_{S_{i*}D_{j1}}, \underbrace{\frac{\gamma_{S_{i*}R_{p*,l*}}\gamma_{R_{q*,l*}D_{j2}}}{\gamma_{S_{i*}R_{p*,l*}} + \gamma_{R_{q*,l*}D_{j2}} + 1}}_{\gamma_{S_{i*}R_{p*,l*,q*}D_{j2}}}\right] < 2^{2R_0} - 1\right\} \\ &= \Pr\left\{\max_{i,j}\gamma_{S_iD_j} < z\right\}\cdot\Pr\left\{\max_{i,p,l,q,j}\gamma_{S_iR_{p,l,q}D_j} < z\right\} \\ &= F_{\lambda_{SD}}(z)\cdot\prod_{l=1}^{M}\Pr\left\{\frac{\max_{i,p,l}\gamma_{S_iR_{p,l}}\cdot\max_{l,q,j}\gamma_{R_{l,q}D_j}}{\max_{i,p,l}\gamma_{S_iR_{p,l}} + \max_{l,q,j}\gamma_{R_{l,q}D_j} + 1} < z\right\} \\ &= F_{\lambda_{SD}}(z)\cdot\underbrace{\prod_{l=1}^{M}\Pr\left\{\frac{\lambda_{SR_l}\cdot\lambda_{R_lD}}{\lambda_{SR_l} + \lambda_{R_lD} + 1} < z\right\}}_{\psi}, \end{aligned} \quad (18)$$

where $z = 2^{2R_0} - 1$, and R_0 is the system transmission rate.

Theorem 1. *The exact outage expression of DAS/SC optimal strategy is given in (19).*

$$\begin{aligned} P_{\text{out}}^{\text{opt-sc}} = {} & \left[1-\exp\left(-\frac{z}{\bar{\gamma}_{SD}}\right)\right]^{N_sN_d}\cdot\prod_{l=1}^{M}\left\{\left[1-\exp\left(-\frac{z}{\bar{\gamma}_{R_lD}}\right)\right]^{N_rN_d} + N_rN_d\cdot\left\{\sum_{j=0}^{N_rN_d-1}\left[\binom{N_rN_d-1}{j}\cdot\frac{(-1)^j}{j+1}e^{-z\cdot(j+1)/\bar{\gamma}_{R_lD}}\right]\right.\right. \\ & \left.\left. + \sum_{i=1}^{N_sN_r}\sum_{j=0}^{N_rN_d-1}\binom{N_sN_r}{i}\binom{N_rN_d-1}{j}(-1)^{i+j}e^{-z\cdot i/\bar{\gamma}_{SR_l}-z\cdot(j+1)/\bar{\gamma}_{R_lD}}\cdot\sqrt{\frac{4i(z^2+z)}{\bar{\gamma}_{SR_l}\cdot\bar{\gamma}_{R_lD}(j+1)}}K_1\left(\sqrt{\frac{4i(j+1)(z^2+z)}{\bar{\gamma}_{SR_l}\cdot\bar{\gamma}_{R_lD}}}\right)\right\}\right\}, \end{aligned} \quad (19)$$

where $K_1(\bullet)$ denotes the modified Bessel function of the second kind.

Proof. See Appendix A. □

The expression is difficult to evaluate the diversity order. So, we analyse asymptotic outage expressions to get the diversity order. First, the analysis of lower bound is considered, which can be derives as

$$P_{\text{out-LB}}^{\text{opt-sc}} = F_{\lambda_{SD}}(z) \cdot \underbrace{\prod_{l=1}^{M} \left[F_{\lambda_{SR_l}}(z) + F_{\lambda_{R_l D}}(z) - F_{\lambda_{SR_l}}(z) \cdot F_{\lambda_{R_l D}}(z) \right]}_{\varphi}. \tag{20}$$

Proof. See Appendix B. □

Now, we concentrate on the behaviour of lower bound in high-SNR regime.

Corollary 2. *Asymptotic expression of φ in high-SNR regime is*

$$\varphi \simeq \sum_{i=0}^{M} \binom{M}{i} \left(\frac{z}{\bar{\gamma}_{SR}} \right)^{N_s N_r (M-i)} \left(\frac{z}{\bar{\gamma}_{RD}} \right)^{N_r N_d i}. \tag{21}$$

Proof. See Appendix C. □

Then, an asymptotically expression for lower bound in high-SNR regime is

$$\begin{aligned} P_{\text{out-LB}}^{\text{opt-sc}} &\overset{\bar{\gamma}\to\infty}{\simeq} \left[1 - \exp\left(-\frac{z}{\bar{\gamma}_{SD}} \right) \right]^{N_s N_d} \cdot \sum_{l=0}^{M} \binom{M}{i} \left(\frac{z}{\bar{\gamma}_{SR}} \right)^{N_s N_r (M-i)} \left(\frac{z}{\bar{\gamma}_{RD}} \right)^{N_r N_d i} \\ &\simeq \left(\frac{z}{\bar{\gamma}_{SD}} \right)^{N_s N_d} \cdot \sum_{l=0}^{M} \binom{M}{l} \left(\frac{z}{\bar{\gamma}_{SR}} \right)^{N_s N_r (M-i)} \left(\frac{z}{\bar{\gamma}_{RD}} \right)^{N_r N_d i} \\ &= \sum_{l=0}^{M} \binom{M}{l} \frac{z^{N_s N_d + N_s N_r (M-l) + N_r N_d l}}{\bar{\gamma}_{SD}{}^{N_s N_d} \cdot \bar{\gamma}_{SR}{}^{N_s N_r (M-l)} \cdot \bar{\gamma}_{RD}{}^{N_r N_d l}}. \end{aligned} \tag{22}$$

For another, an upper bound for (18) is

$$\begin{aligned} P_{\text{out}}^{\text{opt-sc}} &= \Pr\left\{ \max\left[\max_{i,j} \gamma_{S_i D_j}, \max_{i,p,l,q,j} \gamma_{S_i R_{p,l,q} D_j} \right] < 2^{2R_0} - 1 \right\} \simeq \Pr\left\{ \max\left[\max_{i,j} \gamma_{S_i D_j}, \max_{i,p,l,q,j} \frac{\gamma_{S_i R_{p,l}} \gamma_{R_{q,l} D_j}}{\gamma_{S_i R_{p,l}} + \gamma_{R_{q,l} D_j}} \right] < 2^{2R_0} - 1 \right\} \\ &\underset{(e)}{\leq} \Pr\left\{ \max_{i,j} \gamma_{S_i D_j} < z \right\} \cdot \Pr\left\{ \max_{l} \left[\frac{1}{2} \min\left(\max\left(\gamma_{S_i R_{p,l}} \right), \max\left(\gamma_{R_{q,l} D_j} \right) \right) \right] < z \right\} = F_{\lambda_{SD}}(z) \cdot \underbrace{\prod_{l=1}^{M} \left[F_{\lambda_{SR_l}}(2z) + F_{\lambda_{R_l D}}(2z) - F_{\lambda_{SR_l}}(2z) \cdot F_{\lambda_{R_l D}}(2z) \right]}_{\phi} = P_{\text{out-UB}}^{\text{opt-sc}}, \end{aligned} \tag{23}$$

where (e) is obtained according to (B.2).

Similar to φ, ϕ in high-SNR regime is

$$\phi \simeq \sum_{i=0}^{M} \binom{M}{i} \left(\frac{2z}{\bar{\gamma}_{SR}} \right)^{N_s N_r (M-i)} \cdot \left(\frac{2z}{\bar{\gamma}_{RD}} \right)^{N_r N_d i}. \tag{24}$$

Therefore, an asymptotically expression for upper bound in high-SNR regime is

$$P_{\text{out-UB}}^{\text{opt-sc}} \overset{\bar{\gamma}\to\infty}{\simeq} \left[1 - \exp\left(-\frac{z}{\bar{\gamma}_{SD}} \right) \right]^{N_s N_d} \cdot \sum_{i=0}^{M} \binom{M}{i} \left(\frac{2z}{\bar{\gamma}_{SR}} \right)^{N_s N_r (M-i)} \left(\frac{2z}{\bar{\gamma}_{RD}} \right)^{N_r N_d i} \simeq \sum_{i=0}^{M} \binom{M}{i} \frac{z^{N_s N_d} (2z)^{N_s N_r (M-i) + N_r N_d i}}{\bar{\gamma}_{SD}{}^{N_s N_d} \bar{\gamma}_{SR}{}^{N_s N_r (M-i)} \bar{\gamma}_{RD}{}^{N_r N_d i}}. \tag{25}$$

Remark 3. As shown in (22) and (25), the diversity order of DAS/SC optimal strategy is equal to $N_sN_d + MN_r$ min (N_s, N_d).

4.2. DAS/SC Suboptimal Scheme. Mathematica formulation for the outage probability of DAS/SC suboptimal strategy is

$$P_{\text{out}}^{\text{sub-sc}} = \Pr\left\{\frac{1}{2}\log\left(1+\gamma^{i*,l*,q*}\right) < R_0\right\} = \Pr\left\{\frac{1}{2}\log\left(1+\max_{i,j}\left[\gamma_{S_iD_j},\gamma_{S_iR_{p,l,q}D_j}\right]\right) < R_0\right\}. \quad (26)$$

Similar to (19), the closed-form expression of outage probability is

$$\begin{aligned} P_{\text{out}}^{\text{opt-sc}} = {} & \left[1-\exp\left(-\frac{z}{\bar{\gamma}_{SD}}\right)\right]^{N_sN_d} \cdot \prod_{l=1}^{M}\left\{\left[1-\exp\left(-\frac{z}{\bar{\gamma}_{R_lD}}\right)\right]^{N_rN_d} + N_rN_d \cdot \left\{\sum_{j=0}^{N_rN_d-1}\left[\binom{N_rN_d-1}{j}\cdot\frac{(-1)^j}{j+1}e^{-z\cdot(j+1)/\bar{\gamma}_{R_lD}}\right]\right.\right. \\ & \left.\left.+\sum_{i=1}^{N_r}\sum_{j=0}^{N_rN_d-1}\binom{N_r}{i}\binom{N_rN_d-1}{j}(-1)^{i+j}e^{-z\cdot i/\bar{\gamma}_{SR_l}-z\cdot(j+1)/\bar{\gamma}_{R_lD}}\cdot\sqrt{\frac{4i(z^2+z)}{\bar{\gamma}_{SR_l}\cdot\bar{\gamma}_{R_lD}(j+1)}}K_1\left(\sqrt{\frac{4i(j+1)(z^2+z)}{\bar{\gamma}_{SR_l}\cdot\bar{\gamma}_{R_lD}}}\right)\right\}\right\}. \end{aligned} \quad (27)$$

It is not easy to get the exact solution to this probability. Alternatively, lower bound and upper bound for it are derived.

Similarly, lower bound and upper bounds of the DAS/SC suboptimal scheme are

$$P_{\text{out-LB}}^{\text{sub-sc}} = F_{\lambda_{SD}}(z)\cdot\prod_{l=1}^{M}\left[F_{\lambda_{S_{i*}R_l}}(z)+F_{\lambda_{R_lD}}(z)-F_{\lambda_{S_{i*}R_l}}(z)\cdot F_{\lambda_{R_lD}}(z)\right], \quad (28)$$

$$P_{\text{out-UB}}^{\text{sub-sc}} = F_{\lambda_{SD}}(z)\cdot\prod_{l=1}^{M}\left[F_{\lambda_{S_{i*}R_l}}(2z)+F_{\lambda_{R_lD}}(2z)-F_{\lambda_{S_{i*}R_l}}(2z)\cdot F_{\lambda_{R_lD}}(2z)\right]. \quad (29)$$

Asymptotically expressions for the lower and upper bounds in high-SNR regime are

$$P_{\text{out-LB}}^{\text{sub-sc}} \overset{\bar{\gamma}\longrightarrow\infty}{\simeq} \sum_{l=0}^{M}\binom{M}{l}\frac{z^{N_sN_d+N_r(M-l)+N_rN_dl}}{\bar{\gamma}_{SD}{}^{N_sN_d}\cdot\bar{\gamma}_{SR}{}^{N_r(M-l)}\cdot\bar{\gamma}_{RD}{}^{N_rN_dl}}, \quad (30)$$

$$P_{\text{out-UB}}^{\text{sub-sc}} \overset{\bar{\gamma}\longrightarrow\infty}{\simeq} \left[1-\exp\left(-\frac{t}{\bar{\gamma}_{SD}}\right)\right]^{N_sN_d}\cdot\sum_{i=0}^{M}\binom{M}{i}\left(\frac{2z}{\bar{\gamma}_{SR}}\right)^{N_r(M-i)}\left(\frac{2z}{\bar{\gamma}_{RD}}\right)^{N_rN_di} \simeq \sum_{i=0}^{M}\binom{M}{i}\frac{z^{N_sN_d}(2z)^{N_r(M-i)+N_rN_di}}{\bar{\gamma}_{SD}{}^{N_sN_d}\bar{\gamma}_{SR}{}^{N_r(M-i)}\bar{\gamma}_{RD}{}^{N_rN_di}}. \quad (31)$$

Remark 4. As shown in (30) and (31), the diversity order of DAS/SC suboptimal strategy is equal to $N_sN_d + MN_r$ min $(1, N_d)$.

4.3. DAS/LS Scheme. Outage probability of DAS/LS strategy is

$$P_{\text{out}}^{\text{DAS/LS}} = \Pr\left\{\max_{i,j}\gamma_{S_iD_j} < 2^{R_0}-1\right\}\bullet\Pr\left\{\frac{1}{2}\log\left(1+\max_{p,l,q,j}\gamma_{S_{i*}R_{p,l,q}D_j}\right) < R_0\right\}. \quad (32)$$

Again, closed-form expression can be obtained as

$$\begin{aligned} P_{\text{out}}^{\text{opt-sc}} = {} & \left[1-\exp\left(-\frac{2^{R_0}-1}{\bar{\gamma}_{SD}}\right)\right]^{N_sN_d} \cdot \prod_{l=1}^{M}\left\{\left[1-\exp\left(-\frac{z}{\bar{\gamma}_{R_lD}}\right)\right]^{N_rN_d} + N_rN_d \cdot \left\{\sum_{j=0}^{N_rN_d-1}\left[\binom{N_rN_d-1}{j}\cdot\frac{(-1)^j}{j+1}e^{-z\cdot(j+1)/\bar{\gamma}_{R_lD}}\right]\right.\right. \\ & \left.\left.+\sum_{i=1}^{N_r}\sum_{j=0}^{N_rN_d-1}\binom{N_r}{i}\binom{N_rN_d-1}{j}(-1)^{i+j}e^{-z\cdot i/\bar{\gamma}_{SR_l}-z\cdot(j+1)/\bar{\gamma}_{R_lD}}\cdot\sqrt{\frac{4i(z^2+z)}{\bar{\gamma}_{SR_l}\cdot\bar{\gamma}_{R_lD}(j+1)}}K_1\left(\sqrt{\frac{4i(j+1)(z^2+z)}{\bar{\gamma}_{SR_l}\cdot\bar{\gamma}_{R_lD}}}\right)\right\}\right\}. \end{aligned} \quad (33)$$

Again, we analyse its upper and lower bounds. The lower bound is given by

$$P_{\text{out}}^{\text{DAS/LS}} = \left[1 - \exp\left(-\frac{2^{R_0} - 1}{\bar{\gamma}_{SD}}\right)\right]^{N_s N_d} \cdot \Pr\left\{\frac{1}{2}\log\left(1 + \max_{i,p,q,l,j}\left[\gamma_{S_i R_{p,l,q} D_j}\right]\right) < R_0\right\} \simeq F_{\lambda_{SD}}\left(2^{R_0} - 1\right) \cdot \prod_{l=1}^{M}\left[F_{\lambda_{S*R_l}}(z) + F_{\lambda_{R_l D}}(z) - F_{\lambda_{S*R_l}}(z) \cdot F_{\lambda_{R_l D}}(z)\right] \triangleq P_{\text{out-LB}}^{\text{DAS/LS}}. \quad (34)$$

In high-SNR regime, (34) can be expressed as

$$P_{\text{out-LB}}^{\text{DAS/LS}} \overset{\gamma \longrightarrow \infty}{\simeq} \left(\frac{2^{R_0} - 1}{\bar{\gamma}_{SD}}\right)^{N_s N_d} \cdot \sum_{i=0}^{M}\binom{M}{i}\left(\frac{z}{\bar{\gamma}_{SR}}\right)^{N_r(M-i)}\left(\frac{z}{\bar{\gamma}_{RD}}\right)^{N_r N_d i}. \quad (35)$$

On the other hand, the upper bound is

$$P_{\text{out-UB}}^{\text{DAS/LS}} = F_{\lambda_{SD}}\left(2^{R_0} - 1\right) \cdot \prod_{l=1}^{M}\left[F_{\lambda_{SR_l}}(2z) + F_{\lambda_{R_l D}}(2z) - F_{\lambda_{SR_l}}(2z) \cdot F_{\lambda_{R_l D}}(2z)\right] \overset{\gamma \longrightarrow \infty}{\simeq} \left(\frac{2^{R_0} - 1}{\bar{\gamma}_{SD}}\right)^{N_s N_d} \cdot \sum_{i=0}^{M}\binom{M}{i}\left(\frac{2z}{\bar{\gamma}_{SR}}\right)^{N_r(M-i)}\left(\frac{2z}{\bar{\gamma}_{RD}}\right)^{N_r N_d i}. \quad (36)$$

As shown in (35) and (36), the diversity order of DAS/LS scheme is equal to DAS/SC suboptimal one.

Now, we will analysis the mean spectral efficiency of S1 and S2. Assuming the spectral efficiency of the transmission only through direct link R_0. So in the DAS/SC optimal strategy and DAS/SC suboptimal strategy, the spectral efficiency is $R_0/2$ because it spends two slots in transmission. However, the transmission process in DAS/LS scheme is finished in one or two slots which depend on the direct link or relayed link choosing by the transmission. Therefore, in DAS/LS strategy, the spectral efficiency can be expressed as

$$\mathfrak{R} = R_0 \cdot \Pr\left\{\max_{i,j}\gamma_{S_i D_j} > 2^{R_0} - 1\right\} + \frac{R_0}{2} \cdot \Pr\left\{\max_{i,j}\gamma_{S_i D_j} < 2^{R_0} - 1\right\} = R_0 \cdot \left(1 - \left[1 - \exp\left(-\frac{2^{R_0} - 1}{\bar{\gamma}_{SD}}\right)\right]^{N_s N_d}\right) + \frac{R_0}{2} \cdot \left[1 - \exp\left(-\frac{2^{R_0} - 1}{\bar{\gamma}_{SD}}\right)\right]^{N_s N_d}. \quad (37)$$

5. Numerical Results and Discussions

The simulations are executed to verify analytical expressions in this section. Without loss of generality, as in [13], let distance between S and Dd_{SD} normalize to one, and d_{RD} and d_{SR} denote the distance of $R - D$ link and $S - R$ link, respectively. Let transmit power in S the same with which in R, i.e. $P = P_S = P_R$. Therefore, the SNR of these links can be expressed as $\bar{\gamma}_{SD} = Pd_{SD}^{-\beta}/N_0$, $\bar{\gamma}_{SR} = Pd_{SR}^{-\beta}/N_0$, and $\bar{\gamma}_{RD} \triangleq Pd_{RD}^{-\beta}/N_0$, where β denotes link loss exponent. Moreover, set $\beta = 2$ and the target spectral efficiency be $R_0 = 1$bps/Hz. For convenience, we use S1, S2, and S3 represent DAS/SC optimal scheme, DAS/SC suboptimal scheme, and DAS/LS scheme, respectively.

Figure 2 presents the normalized mean spectral efficiency versus $\bar{\gamma}_{SD}$. The number of antennas used at relay and destination is $N_R = N_D = 2$. The mean spectral efficiency of S3 increases with the increase of $\bar{\gamma}_{SD}$, while the spectral efficiency of S1 and S2 is always $R_0/2$. This is because with the increase of $\bar{\gamma}_{SD}$, the probability of $\max_{i,j}\gamma_{S_i D_j} > 2^{R_0} - 1$ is increasing, and the direct link is more likely to be selected for transmission.

Figure 3 is outage performance versus d_{SR} for three proposed schemes with different number of antenna and relay. As we expected, $S1$ is better than $S2$. However, the performance of $S3$ is interesting. One may expect $S3$ is worse than $S2$, because $S3$ preselects the relaying or the direct path before transmission only relied on CSI of direct link, while $S2$ selects the link after transmission according to full CSI. For another, as mentioned in Figure 2, spectral efficiency of $S3$ is better than the other schemes. Furthermore, the SNR threshold of $S3$ decreases when direct link is chosen ($2^{R_0} - 1$ for one slot and $2^{2R_0} - 1$ for two slots). Therefore, $S3$ may outperform $S2$ or $S1$, according to antenna number and relay position in this system, as shown in Figure 3.

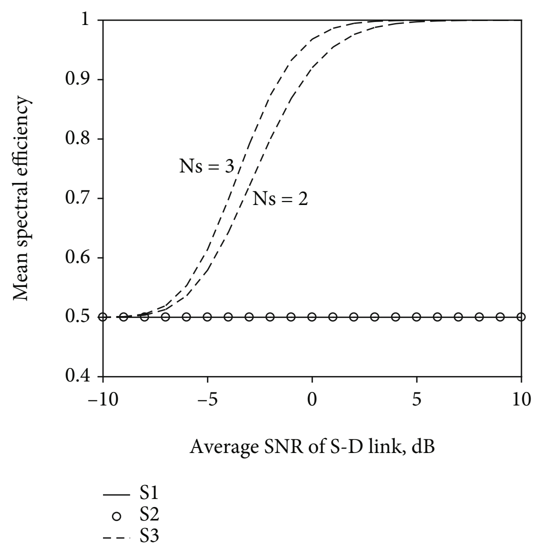

Figure 2: Comparison of proposed strategies in the aspect of spectral efficiency (dSR = 0.5).

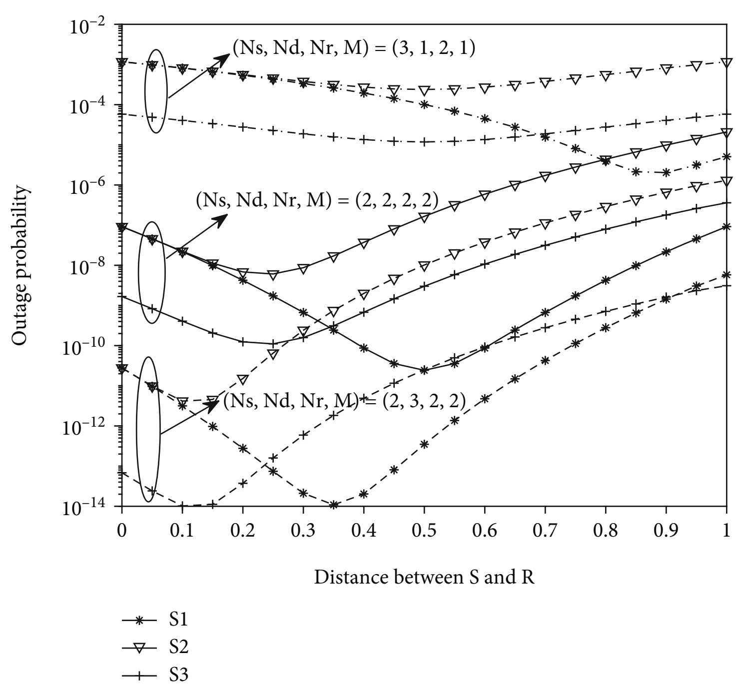

Figure 3: Comparison of proposed strategies in the aspect outage probability (PS/$N0$ = PR/$N0$ = 10 dB).

In Figure 3, for the set of $N_s = N_d$, outage probability of $S1$ reduces with the increase of d_{SR} when $0 < d_{SR} < 0.5$, while the outage probability increases with the increase of d_{SR} when $0.5 < d_{SR} < 1$. So the best performance of $S1$ is achieved when $d_{SR} = 0.5$. And it is figured that the best relay position of $S1$ is closer to the source when $N_s < N_d$, while it is closer to destination when $N_s > N_d$. This behaviour can be explained from (B.2), and the CSI of relaying link almost depends on the worse one between $S - R$ and $R - D$. When $N_s < N_d$, and $d_{SR} = 0.5$, the $S - R$ link is worse than $R - D$, so that the performance will be better when relay is closer to the source. Similar explanation can be used in the behaviour when $N_s > N_d$. In particular, best relay positions for $S1$ are around $d_{SR} \simeq 0.9$ for $N_s = 3$ and $N_d = 1$ and $d_{SR} \simeq 0.35$ for $N_s = 2$ and $N_d = 3$. However, the best relay position of $S2$ and $S3$ is not the same with $S1$, that is because the source transmitting antenna is chosen only by the direct link. And it is only one transmitting antenna for the relaying link. In

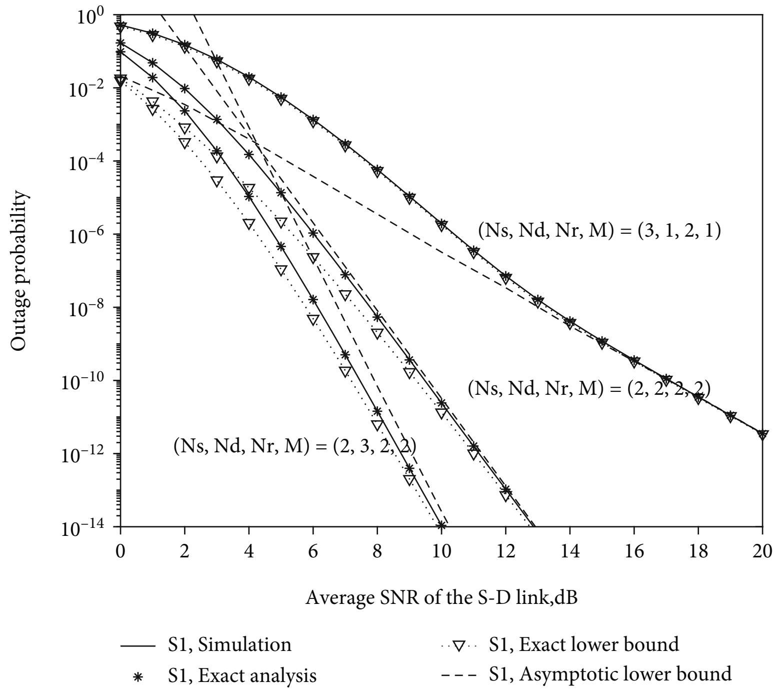

Figure 4: Outage probability versus SNR for $S1$.

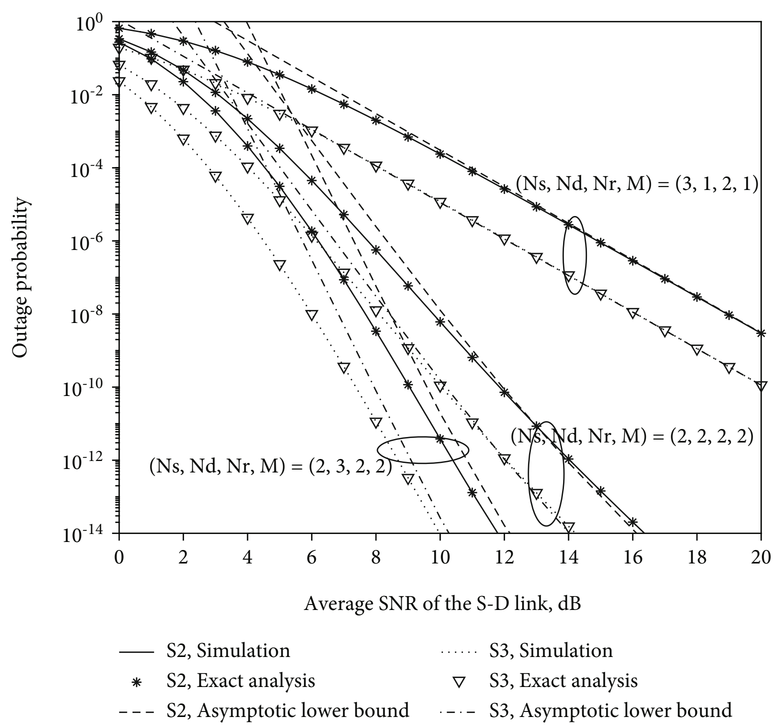

Figure 5: Outage probability versus SNR for $S2$ and $S3$.

particular, best relay positions for $S2$ and $S3$ are around $d_{SR} \simeq 0.5$ for $N_s = 1$ and $N_d = 3$, $d_{SR} \simeq 0.25$ for $N_s = 2$ and $N_d = 2$, and $d_{SR} \simeq 0.1$ for $N_s = 2$ and $N_d = 3$.

The system outage probability of S1 versus SNR with different sets (three scenarios with different antenna number) is conformed in Figure 4. In each scenario, relays have been placed in best relay position which is obtained in Figure 3. In order to verify the theoretical formula for $S1$, analytical results of lower bound and exact expressions are also presented. In this figure, we can see simulation results are close to lower bounds, especially in high SNR range. The outage probability decreases with the increase of antenna number. Moreover, the simulation results are in accordance with asymptotic curves in high SNR regime, which confirm that $S1$ could achieve full diversity order.

Figure 5 is the average system outage probability of $S2$ and $S3$ versus the SNR with different sets (three scenarios with different antenna number). Again, relays have been placed in best relay position according to Figure 3. It can be observed that the system performance of $S3$ is always better than $S2$. Asymptotic curves confirmed that the diversity order of $S2$ and $S3$ is the same, which agree with our theoretical analysis. Furthermore, the more antennas at D, the better the system outage performance. In addition, the system performance improves with the increase of relay number.

6. Conclusions

A multiple-relay MIMO network with direct link has been studied using three amplify-and-forward relaying strategies with antenna and relay selection in this paper. The three strategies are proposed to reduce the implementation complexity and the amount of feedback overhead. Moreover, closed-form outage probability expressions are calculated, as well as the lower and upper asymptotic analytical expressions. The asymptotic results in high-SNR regime reveal the DAS/SC optimal scheme can achieve full diversity order of $N_s N_d + MN_r \min(N_s, N_d)$, while the DAS/SC suboptimal scheme and DAS/LS scheme achieve diversity order of $N_s N_d + MN_r$. Since the DAS/SC suboptimal scheme can select the best transmitting antenna without CSI of SR and RD links. The implementation complexity is less than the DAS/SC optimal scheme at the cost of performance degradation. In addition, mean spectral efficiency of DAS/LS scheme is analysed, which is higher than the other schemes.

Appendix

A. Proof of Theorem 1

ψ can be written as

$$\begin{aligned}
\psi &= \Pr\left\{\frac{\lambda_{SR_l}\cdot\lambda_{R_lD}}{\lambda_{SR_l}+\lambda_{R_lD}+1} < z\right\} = \Pr\left\{\lambda_{SR_l}\cdot\left(\lambda_{R_lD}-z\right) < \left(\lambda_{R_lD}+1\right)\cdot z\right\} = \Pr\left\{\lambda_{R_lD} < z\right\} + \Pr\left\{\lambda_{R_lD}\geq z, \lambda_{SR_l} < \frac{\left(\lambda_{R_lD}+1\right)\cdot z}{\lambda_{R_lD}-z}\right\} \\
&= F_{\lambda_{R_lD}}(z) + \int_z^{\infty} F_{\lambda_{SR_l}}\left(\frac{(t+1)\cdot z}{t-z}\right)\cdot f_{\lambda_{R_lD}}(t)dt \overset{(a)}{=} F_{\lambda_{R_lD}}(z) + \frac{N_r N_d}{\bar{\gamma}_{R_lD}}\int_z^{\infty}\sum_{i=0}^{N_sN_r}\sum_{j=0}^{N_rN_d-1}\binom{N_sN_r}{i}\binom{N_rN_d-1}{j}(-1)^{i+j}e^{-(t+1)\cdot z\cdot i/\bar{\gamma}_{SR_l}(t-z)-t\cdot j/\bar{\gamma}_{R_lD}-t/\bar{\gamma}_{R_lD}}dt \\
&= F_{\lambda_{R_lD}}(z) + \frac{N_r N_d}{\bar{\gamma}_{R_lD}}\cdot\sum_{i=0}^{N_sN_r}\sum_{j=0}^{N_rN_d-1}\binom{N_sN_r}{i}\binom{N_rN_d-1}{j}(-1)^{i+j}e^{-z\cdot i/\bar{\gamma}_{SR_l}-z\cdot(j+1)/\bar{\gamma}_{R_lD}}\int_0^{\infty}e^{-\left(z^2+z\right)\cdot i/\bar{\gamma}_{SR_l}\cdot x-x\cdot(j+1)/\bar{\gamma}_{R_lD}}dx \\
&\overset{(b)}{=} F_{\lambda_{R_lD}}(z) + N_rN_d\cdot\left\{\sum_{j=0}^{N_rN_d-1}\left[\binom{N_rN_d-1}{j}\cdot\frac{(-1)^{i+j}}{j+1}e^{-z\cdot(j+1)/\bar{\gamma}_{R_lD}}\right] + \sum_{i=1}^{N_sN_r}\sum_{j=0}^{N_rN_d-1}\binom{N_sN_r}{i}\binom{N_rN_d-1}{j}(-1)^{i+j}e^{-z\cdot i/\bar{\gamma}_{SR_l}-z\cdot(j+1)/\bar{\gamma}_{R_lD}}\cdot\sqrt{\frac{4i(z^2+z)}{\bar{\gamma}_{SR_l}\cdot\bar{\gamma}_{R_lD}(j+1)}}K_1\left(\sqrt{\frac{4i(j+1)(z^2+z)}{\bar{\gamma}_{SR_l}\cdot\bar{\gamma}_{R_lD}}}\right)\right\},
\end{aligned} \tag{A.1}$$

where (a) uses Binomial theorem, and (b) is calculated with the help of ([22], Eq. (3.324.1)). (20) can be obtained by plugging (A.1) into (18)

B. Lower-Bound Expression for DAS/SC Optimal Scheme

$$\begin{aligned}
P_{\text{out}}^{\text{opt-sc}} &= \Pr\left\{\max\left[\max_{i,j}\gamma_{S_iD_j}, \max_{i,p,l,q,j}\gamma_{S_iR_{p,l,q}D_j}\right] < 2^{2R_0}-1\right\} \simeq \Pr\left\{\max\left[\max_{i,j}\gamma_{S_iD_j}, \max_{i,p,l,q,j}\frac{\gamma_{S_iR_{p,l}}\gamma_{R_{q,l}D_j}}{\gamma_{S_iR_{p,l}}+\gamma_{R_{q,l}D_j}}\right] < 2^{2R_0}-1\right\} \\
&\underset{(c)}{\geq} \Pr\left\{\max\left[\max_{i,j}\gamma_{S_iD_j}, \max_{i,p,l,q,j}\left[\min\left(\gamma_{S_iR_{p,l}}, \gamma_{R_{q,l}D_j}\right)\right]\right] < z\right\} = \Pr\left\{\max\left[\lambda_{SD}, \max_{l}\left[\min\left(\lambda_{SR_l}, \lambda_{R_lD}\right)\right]\right] < z\right\} \\
&\triangleq P_{\text{out-LB}}^{\text{opt-sc}} = F_{\lambda_{SD}}(z)\cdot\prod_{l=1}^{M}F_{\lambda_l}(z) \underset{(d)}{=} F_{\lambda_{SD}}(z)\cdot\underbrace{\prod_{l=1}^{M}\left[F_{\lambda_{SR_l}}(z)+F_{\lambda_{R_lD}}(z)-F_{\lambda_{SR_l}}(z)\cdot F_{\lambda_{R_lD}}(z)\right]}_{\varphi},
\end{aligned} \tag{B.1}$$

where (c) is given as follow [11]:

$$\frac{1}{2}\min\left(\gamma_{S_iR_{p,l}},\gamma_{R_{q,l}D_j}\right)\le\frac{\gamma_{S_iR_{p,l}}\gamma_{R_{q,l}D_j}}{\gamma_{S_iR_{p,l}}+\gamma_{R_{q,l}D_j}}\le\min\left(\gamma_{S_iR_{p,l}},\gamma_{R_{q,l}D_j}\right). \tag{B.2}$$

And (d) is given as follows:

$$F_{\lambda_l}(t)=\Pr(\lambda_l<t)=\Pr\left(\min\left(\lambda_{SR_l},\lambda_{R_lD}\right)<t\right)=1-\left[1-\Pr\left(\lambda_{SR_l}<t\right)\right]\cdot\left[1-\Pr\left(\lambda_{R_lD}<t\right)\right]=F_{\lambda_{SR_l}}(t)+F_{\lambda_{R_lD}}(t)-F_{\lambda_{SR_l}}(t)\cdot F_{\lambda_{R_lD}}(t). \tag{B.3}$$

C. Proof of Corollary 1

In the high-SNR regime, using the approximate formula $e^{-\alpha}\simeq^{\alpha\longrightarrow 0}1-\alpha$, and employing the lowest order terms corresponding to $1/\bar{\gamma}$, φ can be asymptotically expressed as

$$\varphi\simeq\left[F_{\lambda_{SR_l}}(z)+F_{\lambda_{R_lD}}(z)\right]^M=\left[\left[1-\exp\left(-\frac{z}{\bar{\gamma}_{SR}}\right)\right]^{N_sN_r}+\left[1-\exp\left(-\frac{z}{\bar{\gamma}_{RD}}\right)\right]^{N_rN_d}\right]^M \overset{\bar{\gamma}\longrightarrow\infty}{\simeq}\left[\left(\frac{z}{\bar{\gamma}_{SR}}\right)^{N_sN_r}+\left(\frac{z}{\bar{\gamma}_{RD}}\right)^{N_rN_d}\right]^M=\sum_{i=0}^{M}\binom{M}{i}\left(\frac{z}{\bar{\gamma}_{SR}}\right)^{N_sN_r(M-i)}\left(\frac{z}{\bar{\gamma}_{RD}}\right)^{N_rN_di}. \tag{C.1}$$

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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