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Dual Relay Selection for Cooperative NOMA With Distributed Space Time Coding

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ABSTRACT We consider a two-user multi-relay cooperative non-orthogonal multiple access (NOMA) network with distributed space–time coding. Two dual-relay selection strategies are proposed for cooperative NOMA, namely, *two-stage dual relay selection with fixed power allocation* (DRS-FPA) and *two-stage dual relay selection with dynamic power allocation* (DRS-DPA). Furthermore, lower and upper bounds on the outage probability for the DRS-FPA scheme and the exact outage probability for the DRS-DPA scheme are obtained in closed-form, respectively. Numerical results show that the proposed two-stage DRS schemes not only yield better outage performance than the existing single relay selection schemes without sacrificing spectral efficiency, but can also achieve full diversity gain.

INDEX TERMS Cooperative non-orthogonal multiple access, relay selection, space time coding, outage performance.

I. INTRODUCTION

Non-orthogonal multiple access (NOMA) has recently received enormous interest as a promising candidate to significantly boost the spectral efficiency of the fifth generation (5G) wireless networks [1]–[4]. On the other hand, cooperative diversity can combat fading, extend service coverage, improve system capacity and achieve spatial degrees of freedom even if the nodes are equipped with a single antenna [5], [6]. Then, cooperative NOMA is an emerging and important topic, where users or dedicated relays cooperate in order to improve the transmission reliability.

The idea of user cooperation for NOMA was firstly proposed in [7], where successive interference cancellation (SIC) is implemented at the user with good channel conditions, in order to decode the signals for the users with poor channel conditions, and then the strong user acts as a relay to assist the weak user. In [8], a dedicated relay has been used for a two-user NOMA system to enhance the performance of the user. Unlike the existing work, in [9] and [10], users are not ordered by using their channel conditions, but categorized through their quality of service (QoS) requirements. A two-stage single relay selection with fixed power allocation (SRS-FPA) was introduced for cooperative NOMA [9]. In this work, the provided simulations and analytical results show that the outage performance of this scheme outperforms that of the conventional max-min strategy and can also yield a significant performance gain over orthogonal multiple access (OMA). In order to further improve the outage performance, a two-stage single-relay-selection with half-dynamic power allocation (SRS-half-DPA) [10] was proposed, i.e., during the first stage a relay subset is selected, which can successfully decode all the users' messages, as well as the user with a lower data rate can be strictly satisfied, while maximizing its partner's rate in the second stage.

Although multiple relay selection (MRS) schemes [11], [12] can achieve a better outage performance than the SRS scheme, their spectral efficiencies are limited, due to the orthogonality between multiple relays to avoid inter-relay interference (IRI). In addition, the complexity exponentially increases with the available number of relays. Therefore, dual relaying selection (DRS) is good choice. In order to deal with the loss of spectral efficiency induced by DRS, distributed space time coding (DSTC) can be used at relays, that is, DRS for cooperative NOMA with DSTC could offer a good tradeoff between outage performance and spectral efficiency. Two DRS schemes with different STCs in the two-way amplify-and-forward (AF) relay channel, was analyzed in [13] and [14], respectively. However, these works do not consider the NOMA approach. To the best of the authors' knowledge, in the open literature, there are few MRS schemes, proposed for cooperative NOMA and employing space time coding. Recall that diversity gains can be achieved by space-time coding at the transmitter side, which requires only simple linear processing at the receiver side for decoding [15]. Using the Alamouti code by the two selected relays for DRS scheme, IRI does not exist anymore, which is attributed to complex orthogonality of the transmitted signals. A cooperative decode-and-forward (DF) relaying scheme based on Alamouti space time block coded NOMA, was proposed in [16]. In this work, it has been pointed out that the cooperative relaying system (CRS) using STC-NOMA can attain a significant performance gain compared to conventional CRS-NOMA and the traditional DF relaying schemes. Two DRS schemes for cooperative NOMA with DSTC are investigated in this paper to extend the CRS-STC-NOMA into general networks with multiple relays and multiple users, which can further improve the system performance and achieve higher diversity gain.

The main contributions of this paper can be summarized as follow:

1) A novel two-stage DF dual relay selection with fixed power allocation (DRS-FPA) and space time coding for two-user cooperative NOMA is proposed, where a relay set can successfully decode both signals for U_1 and U_2 at stage 1, while choosing the two best available relays according to the max-min criterion, at the second stage. Furthermore, exact closed-form expressions for the lower and upper bounds of the outage probability for the two-stage DRS-FPA scheme, are derived. Numerical results show that the outage performance of the proposed scheme is superior to that of the SRS-FPA strategy [9], without loss of spectral efficiency.
2) In order to further improve the system performance, the two-stage DF single and dual relay selection schemes, with dynamic power allocation (SRS-DPA and DRS-DPA), are presented, where DPA is used for both hops instead for the second hop only, as in [10]. Furthermore, we obtain exact expressions for the outage probability of the two schemes. It is noted that the proposed SRS-DPA and DRS-DPA schemes significantly outperform the SRS-half-DPA scheme [10].
3) The analytical results and simulations demonstrate that all the proposed schemes, such as DRS-FPA, SRS-DPA and DRS-DPA, can achieve maximum diversity gain. In addition, the outage performance gap between the DRS and SRS schemes becomes larger with a decrease in the difference of the user 1's and user 2's target data rates or with an increase in the number of the relays.

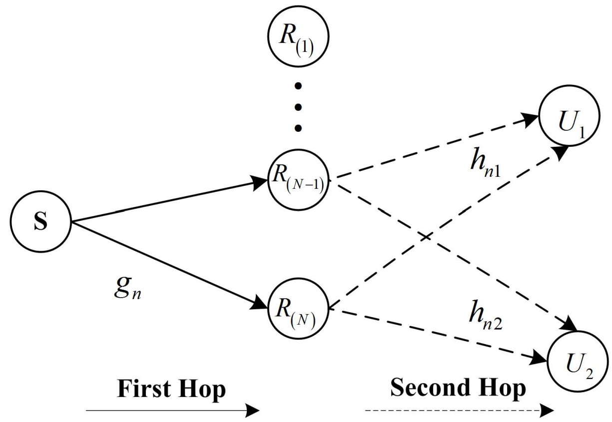

FIGURE 1. System model.

The rest of this paper is organized as follows. Section II introduces the system model of cooperative NOMA with space time coding and the proposed relay selection schemes. The outage probabilities for the DRS-FPA, SRS-DPA and DRS-DPA schemes are developed in Section III. Numerical results are presented in Section IV to illustrate the performance of the proposed schemes. Finally, the conclusion of this paper is drawn in Section V.

II. SYSTEM MODEL

Consider a two-user cooperative NOMA network consisting of a source S, e.g., a base station (BS), N half-duplex relays R, and two users U_1 and U_2, as depicted in Fig. 1. Assume that the BS, relays and users are all equipped with a single antenna. It is assumed that no direct link between the BS and users exists, due to obstacles or heavy shadowing, and the relays assist the users to communicate with the BS. We further assume that the channel of each link is modeled as identically and independent distributed (i.i.d) Rayleigh fading. Similar to [9] and [10], we assume that the users are ordered according to their QoS requirements rather than their channel conditions. Particularly, we assume that user 1 has a higher priority than user 2 to be served, i.e., user 1 prefers quick connection with a low data rate, such as Internet of Things (IoT) sensors, while user 2 would like a high resolution for online game or downloading a movie. The detailed model and relay selection schemes for the cooperative NOMA network will be presented in the following two subsections, respectively.

A. COOPERATIVE NOMA WITH DSTC

In order to implement space-time coding in the cooperative NOMA network, two relays are selected in the proposed scheme, and perfect synchronization between relays is assumed.[1] The details for the relay selection will be discussed

[1]It is also interesting to investigate special codes in order to achieve the full asynchronous cooperative diversity order as in [17] and the references therein. However, this is out of the scope of this paper.

TABLE 1. DSTC for DF cooperative NOMA.

	$R_{(N)}$	$R_{(N-1)}$
t_3 :	$z_1 = \alpha_1 s_{11} + \alpha_2 s_{12}$	$z_2 = \alpha_1 s_{21} + \alpha_2 s_{22}$
t_4 :	$-z_2^* = -\alpha_1 s_{21}^* - \alpha_2 s_{22}^*$	$z_1^* = \alpha_1 s_{11}^* + \alpha_2 s_{12}^*$

in Section II-B. The transmission for the proposed cooperative NOMA network with DSTC consists of two phases: during Phase I, the BS broadcasts the superimposed mixture x_1 and x_2 at two successive time slot t_1 and t_2 to N relays, respectively, as follows:

$$t_1 : x_1 = \alpha_1 s_{11} + \alpha_2 s_{12}, \tag{1}$$
$$t_2 : x_2 = \alpha_1 s_{21} + \alpha_2 s_{22}, \tag{2}$$

where s_{ij} $(i, j \in \{1, 2\})$ is the signal for U_j at time slot t_i and α_i denotes the power allocation coefficient. Note that $\alpha_1^2 + \alpha_2^2 = 1$ and $\alpha_1 \geq \alpha_2$ according to the NOMA principle, i.e., more power is assigned to the user with a worse channel condition or a lower data rate QoS requirement [7], [9]. It is noted that the symbols s_{11}, s_{21} and s_{12}, s_{22} are transferred to user 1 and 2 via the relaying links, respectively. It means that although two time slots are used for the source-to-relay (S-R) links, in the mean time, two different information signals can also be transmitted to user 1 and user 2, respectively, which is equivalent to the one time slot scheme used in [9], where only one symbol is transmitted to users.

Therefore, the signals received by the relay R_n, $n \in \{1, \cdots, N\}$, are:

$$t_1 : y_n^1 = g_n x_1 + n_{R_n}, \tag{3}$$
$$t_2 : y_n^2 = g_n x_2 + n_{R_n}, \tag{4}$$

where $g_n \sim \mathcal{CN}\left(0, \sigma_{g_n}^2\right)$ denotes the channel coefficient between the BS and relay n, and the noise n_{R_n} is the additive white Gaussian noise with zero mean and variance of N_0.

Assume that SIC can be successfully preformed at relays. Therefore, the achievable rates for relay n to decode the signals of user 1 and user 2 are given by

$$R_{1\to \mathrm{R}}^{\mathrm{DF}} = \frac{1}{2}\log_2\left(1 + \frac{\alpha_1^2|g_n|^2}{\alpha_2^2|g_n|^2 + 1/\rho}\right), \tag{5}$$
$$R_{2\to \mathrm{R}}^{\mathrm{DF}} = \frac{1}{2}\log_2\left(1 + \rho\alpha_2^2|g_n|^2\right), \tag{6}$$

where ρ denotes the transmit signal-to-noise ratio (SNR), and $R_{i\to \mathrm{R}}^{\mathrm{DF}}$ denotes the instantaneous data rate for user i achieved at relay n.

During Phase II, the relay nodes $R_{(N)}$ and $R_{(N-1)}$ are selected according to the DRS criterion in Section II-B. For the DF relaying, we assume that the two selected relays can decode both the signals for U_1 and U_2 correctly and then retransmit the encoded NOMA signals to user 1 and user 2 by using the Alamouti code, as shown in Table 1.

The received signals at user i, $i \in \{1, 2\}$ can be derived as:

$$t_3 : r_i^1 = h_{(N)i} z_1 + h_{(N-1)i} z_2 + n_{D_i}, \tag{7}$$
$$t_4 : r_i^2 = -h_{(N)i} z_2^* + h_{(N-1)i} z_1^* + n_{D_i}, \tag{8}$$

where $h_{ni} \sim \mathcal{CN}\left(0, \sigma_{h_{ni}}^2\right)$ denotes the channel gain from relay n to user i, and the noise n_{D_i} is the additive white Gaussian noise with zero mean and variance of N_0.

Then the decoding symbols at user i are given by

$$\tilde{s}_{1i} = h_{(N)i}^* r_i^1 + h_{(N-1)i} r_i^{2*}, \tag{9}$$
$$\tilde{s}_{2i} = h_{(N-1)i}^* r_i^1 - h_{(N)i} r_i^{2*}. \tag{10}$$

Furthermore, (9) and (10) can be written as:

$$\tilde{s}_{1i} = \left(|h_{(N)i}|^2 + |h_{(N-1)i}|^2\right)(\alpha_1 s_{11} + \alpha_2 s_{12}) + h_{(N)i}^* n_{D_i} + h_{(N-1)i} n_{D_i}^*, \tag{11}$$
$$\tilde{s}_{2i} = \left(|h_{(N)i}|^2 + |h_{(N-1)i}|^2\right)(\alpha_1 s_{21} + \alpha_2 s_{22}) + h_{(N)i}^* n_{D_i} - h_{(N-1)i} n_{D_i}^*. \tag{12}$$

Then the achievable instantaneous data rates for user 1 and user 2 at users can be expressed as:

$$R_1^{\mathrm{DF}} = \frac{1}{2}\log_2\left(1 + \frac{\alpha_1^2\left(|h_{(N)1}|^2 + |h_{(N-1)1}|^2\right)}{\alpha_2^2\left(|h_{(N)1}|^2 + |h_{(N-1)1}|^2\right) + 1/\rho}\right), \tag{13}$$
$$R_{1\to 2}^{\mathrm{DF}} = \frac{1}{2}\log_2\left(1 + \frac{\alpha_1^2\left(|h_{(N)2}|^2 + |h_{(N-1)2}|^2\right)}{\alpha_2^2\left(|h_{(N)2}|^2 + |h_{(N-1)2}|^2\right) + 1/\rho}\right), \tag{14}$$
$$R_2^{\mathrm{DF}} = \frac{1}{2}\log_2\left(1 + \rho\alpha_2^2\left(|h_{(N)2}|^2 + |h_{(N-1)2}|^2\right)\right), \tag{15}$$

where R_i^{DF} is the achievable data rate for user i to detect its own signal, SIC is carried out at user 2 to remove the signal for user 1, and $R_{1\to 2}^{\mathrm{DF}}$ is the instantaneous rate for user 2 to detect the signal for user 1.

For the single relay selection case, the corresponding instantaneous data rates at users can be written as:

$$R_1^{\mathrm{DF}_1} = \frac{1}{2}\log_2\left(1 + \frac{\alpha_1^2|h_{(N)1}|^2}{\alpha_2^2|h_{(N)1}|^2 + 1/\rho}\right), \tag{16}$$
$$R_{1\to 2}^{\mathrm{DF}_1} = \frac{1}{2}\log_2\left(1 + \frac{\alpha_1^2|h_{(N)2}|^2}{\alpha_2^2|h_{(N)2}|^2 + 1/\rho}\right), \tag{17}$$
$$R_2^{\mathrm{DF}_1} = \frac{1}{2}\log_2\left(1 + \rho\alpha_2^2|h_{(N)2}|^2\right). \tag{18}$$

It is obvious that the data rates in (13), (14) and (15) are always higher than those in (16), (17) and (18). This clearly demonstrates that the proposed DRS schemes have better performance than the existing SRS schemes.

B. RELAY SELECTION SCHEMES

In this section, we mainly focus on two DRS schemes, which can significantly enhance the outage performance at the cost of a little overhead. Two-stage DF DRS-FPA strategy is firstly considered. In the proposed scheme, the first and second best

Algorithm 1 Two-Stage DSR-FPA Scheme

if $|S_r| == 0$ **then**
  System in outage
else if $|S_r| == 1$ **then**
  Only one relay is available
  if $R_1^{\mathrm{DF}_1} \geq R_1$ **and** $R_{1\to 2}^{\mathrm{DF}_1} \geq R_1$ **and** $R_2^{\mathrm{DF}_1} \geq R_2$ **then**
    Success transmission
  else
    System in outage
  end if
else
  Sort $\min(|h_{n1}|^2, |h_{n2}|^2), n \in S_r$, choose the 1st and 2nd best relay.
  if $R_1^{\mathrm{DF}} \geq R_1$ **and** $R_{1\to 2}^{\mathrm{DF}} \geq R_1$ **and** $R_2^{\mathrm{DF}} \geq R_2$ **then**
    Success transmission
  else
    System in outage
  end if
end if

relays will be chosen simultaneously instead of selecting the best relay, as in [9]. Furthermore, two-stage DF SRS-DPA and DRS-DPA schemes are presented to improve the performance, where dynamic power allocation is used for both S-R and relay-to-destination (R-D) links rather than only in the R-D link in [10].

1) TWO-STAGE DRS-FPA SCHEME

In order to realize the Almouti code in the dual relay selection strategy, the two selected relays need to successfully decode the messages for user 1 and user 2 simultaneously, i.e., the instantaneous data rates for U_1 and U_2 are larger or equal to their target data rates R_1 and R_2, respectively. Therefore, for the two-stage scheme, the first stage is to build a successful decoding subset S_r depending on the decoding status of the relays, which is different from the scheme in [9] that only ensure the user with lower data rate strictly, i.e. user 1, at the first stage. Assuming that SIC is performed at the relays, then the subset of the relays which satisfy the user 1's and user 2's target data rates can be defined as follows:

$$S_r = \Bigg\{n : 1 \leq n \leq N, \frac{1}{2}\log_2\left(1+\rho\alpha_2^2|g_n|^2\right) \geq R_2, \frac{1}{2}\log_2\left(1+\frac{\alpha_1^2|g_n|^2}{\alpha_2^2|g_n|^2+1/\rho}\right) \geq R_1\Bigg\}. \quad (19)$$

In the second stage the relay is selected according to the size of S_r, denoted as $|S_r|$. The detailed algorithm is shown in Algorithm 1.

2) TWO-STAGE SRS/DRS-DPA SCHEME

In order to further improve the performance, dynamic power allocation is used in this scheme. Different from the DRS-FPA scheme, at the first stage, there are two conditions for the available relays. One is that the relay can successfully decode the messages for both users, the other one is the user with lower QoS requirement, i.e. U_1, can be strictly satisfied, and then try to maximize another user's rate at the second stage.

It is well-known that the conditions for a relay to decode the two signals correctly are given by

$$\frac{1}{2}\log_2\left(1+\frac{\alpha_1^2|g_n|^2}{\alpha_2^2|g_n|^2+1/\rho}\right) \geq R_1, \quad \frac{1}{2}\log_2\left(1+\alpha_2^2\rho|g_n|^2\right) \geq R_2. \quad (20)$$

Based on (20), the range of the power allocation factor α_2^2 can be expressed as:

$$\frac{\epsilon_2}{\rho|g_n|^2} \leq \alpha_2^2 \leq \frac{|g_n|^2 - \frac{\epsilon_1}{\rho}}{|g_n|^2(1+\epsilon_1)}, \quad (21)$$

where $\epsilon_i = 2^{2R_i} - 1, i \in 1, 2$. Note that if we choose the value of α_2^2 according to (21), we can ensure that the messages for user 1 and user 2 can be decoded correctly at the relay n.

Recall that the QoS requirement of user 1 needs to be strictly satisfied in the first stage, which yields that

$$\frac{1}{2}\log_2\left(1+\frac{\alpha_1^2|h_{n1}|^2}{\alpha_2^2|h_{n1}|^2+1/\rho}\right) \geq R_1. \quad (22)$$

Using (22), the maximal power allocation factor α_2^2 can be written as:

$$\alpha_2^2 = \min\left\{\frac{|g_n|^2 - \frac{\epsilon_1}{\rho}}{|g_n|^2(1+\epsilon_1)}, \frac{|h_{n1}|^2 - \frac{\epsilon_1}{\rho}}{|h_{n1}|^2(1+\epsilon_1)}\right\}. \quad (23)$$

Note that only if the value of α_2^2 in (23) is lager or equal to $\frac{\epsilon_2}{\rho|g_n|^2}$, the conditions in (20) and (22) are always satisfied.

As described above, the subset of the active relays can be obtained by

$$S_r = \left\{n : |g_n|^2 \geq \frac{a_2}{\rho}, |h_{n1}|^2 \geq \frac{\epsilon_1|g_n|^2}{\rho|g_n|^2 - a_1}\right\}, \quad (24)$$

where $a_1 = \epsilon_2(1+\epsilon_1)$ and $a_2 = \epsilon_1 + \epsilon_2(1+\epsilon_1)$.

For the SRS-DPA scheme, only the best relay in S_r is selected to serve U_2 at the second stage, and the selection criterion can be defined as

$$n^* = \arg\max_{n\in S_r}\left\{|h_{n2}|^2\right\}. \quad (25)$$

For the DRS-DPA scheme, the second stage is to choose two best relays among S_r which can maximize the data rate for U_2. Sort $|h_{n2}|^2$ in an ascending order, which is denoted by $|h_{(1)2}|^2 \leq \cdots \leq |h_{(N-1)2}|^2 \leq |h_{(N)2}|^2$. The relay nodes $R_{(N)}$ and $R_{(N-1)}$ corresponding to $|h_{(N)2}|^2$ and $|h_{(N-1)2}|^2$ will be selected. Define $\gamma_{\mathrm{sum}} \triangleq |h_{(N)2}|^2 + |h_{(N-1)2}|^2$. In addition, there is a constraint for user 2 to achieve a high data rate, that is, SIC can be successfully carried out at user 2 for both SRS-DPA and DRS-DPA schemes, i.e., $\frac{1}{2}\log_2\left(1+\frac{\alpha_1^2|h_{n^*2}|^2}{\alpha_2^2|h_{n^*2}|^2+1/\rho}\right) \geq R_1$

and $\frac{1}{2}\log_2\left(1+\frac{\alpha_1^2\gamma_{\text{sum}}}{\alpha_2^2\gamma_{\text{sum}}+1/\rho}\right) \geq R_1$, respectively. (For the case $|S_r| = 1$ in the DRS-DPA scheme, just using $|h_{(N)2}|^2$ instead of γ_{sum}, which is omitted here). Then the maximal power allocation factor α_2^2 can be updated by

$$\text{temp} = \min\left\{\frac{|g_{n^*}|^2 - \frac{\epsilon_1}{\rho}}{|g_{n^*}|^2(1+\epsilon_1)}, \frac{|h_{n^*1}|^2 - \frac{\epsilon_1}{\rho}}{|h_{n^*1}|^2(1+\epsilon_1)}\right\},$$
$$\alpha_2^{2|\text{SRS}} = \min\left\{\text{temp}, \frac{|h_{n^*2}|^2 - \frac{\epsilon_1}{\rho}}{|h_{n^*2}|^2(1+\epsilon_1)}\right\}, \quad (26)$$
$$\text{temp}_1 = \min\left\{\frac{|g_{(N)}|^2 - \frac{\epsilon_1}{\rho}}{|g_{(N)}|^2(1+\epsilon_1)}, \frac{|h_{(N)1}|^2 - \frac{\epsilon_1}{\rho}}{|h_{(N)1}|^2(1+\epsilon_1)}\right\},$$
$$\text{temp}_2 = \min\left\{\frac{|g_{(N-1)}|^2 - \frac{\epsilon_1}{\rho}}{|g_{(N-1)}|^2(1+\epsilon_1)}, \frac{|h_{(N-1)1}|^2 - \frac{\epsilon_1}{\rho}}{|h_{(N-1)1}|^2(1+\epsilon_1)}\right\},$$
$$\alpha_2^{2|\text{DRS}} = \min\left\{\text{temp}_1, \text{temp}_2, \frac{\gamma_{\text{sum}} - \frac{\epsilon_1}{\rho}}{\gamma_{\text{sum}}(1+\epsilon_1)}\right\}. \quad (27)$$

It is evident from (26) and (27) that the power allocation coefficient α_2 is related to the target data rate of user 1 and the channel fading gains for the selected S-R and R-D links. Furthermore, it is remarkable that if the final value of the power allocation factor $\alpha_2 < \frac{\epsilon_2}{\rho|g_n|^2}$, the system outage will happen, and the impact of this constraint will be taken into consideration for the evaluation of the outage probability.

III. OUTAGE PERFORMANCE ANALYSIS

In this section, the system outage probabilities of the considered DRS-FPA, SRS-DPA and DRS-DPA schemes are analyzed. The system outage probability can be defined as follows:

$$P_{\text{out}} = P(|S_r| = 0) + \sum_{l=1}^{N} P(|S_r| = l) P_l, \quad (28)$$

where P_l is the condition outage probability when the size of the active relays set equals to l.

For the DRS-FPA scheme, when $l = 1$, by using the fact that all channels are assumed to be i.i.d Rayleigh fading, the coverage probability $\bar{P}_1$ can be calculated as:

$$\bar{P}_1 = P\left\{R_1^{\text{DF}_1} \geq R_1,\ R_{1\to 2}^{\text{DF}_1} \geq R_1,\ R_2^{\text{DF}_1} \geq R_2 \middle| |S_r| = 1\right\}$$
$$= P\left\{|h_{(N)1}|^2 \geq \xi_1/\rho,\ |h_{(N)2}|^2 \geq \eta/\rho\right\} = e^{-\frac{a}{\rho}}, \quad (29)$$

where $\xi_1 = \frac{\epsilon_1}{\alpha_1^2 - \epsilon_1\alpha_2^2}$, $\xi_2 = \frac{\epsilon_2}{\alpha_2^2}$, $\eta = \max\{\xi_1, \xi_2\}$ and $a = \xi_1 + \eta$. It is assumed that $\alpha_1^2 > \epsilon_1\alpha_2^2$, which always leads to the system in outage, when a wrong choice for the power allocation coefficient is used.

When $l \geq 2$, the relay nodes $R_{(l)}$ and $R_{(l-1)}$ will be selected to assist the communication with U_1 and U_2. Similar to the case of $l = 1$, the coverage probability $\bar{P}_l$ can be written as:

$$\bar{P}_l = P\left\{|h_{(l)1}|^2 + |h_{(l-1)1}|^2 \geq \frac{\xi_1}{\rho},\ |h_{(l)2}|^2 + |h_{(l-1)2}|^2 \geq \frac{\eta}{\rho}\right\}. \quad (30)$$

It is difficult to obtain the exact distribution of the term $|h_{(l)i}|^2 + |h_{(l-1)i}|^2$, $i = 1, 2$ in (30), therefore, the lower and upper bounds are introduced in the following. Let $\gamma_i = \min\{|h_{i1}|^2, |h_{i2}|^2\}$, $\beta_i = \max\{|h_{i1}|^2, |h_{i2}|^2\}$, $i \in S_r$, then rearrange $\gamma_i, \beta_i, (i = 1, \cdots, l)$ in an ascending order, which is denoted by $\gamma_{(i)}, \beta_{(i)}$, such that $\gamma_{(1)} \leq \cdots \leq \gamma_{(l-1)} \leq \gamma_{(l)}$ and $\beta_{(1)} \leq \cdots \leq \beta_{(l'-1)} \leq \beta_{(l')}$. It can be seen from (30) that

$$|h_{(l)i}|^2 + |h_{(l-1)i}|^2 \geq \gamma_{(l)} + \gamma_{(l-1)}, \quad (31)$$
$$|h_{(l)i}|^2 + |h_{(l-1)i}|^2 \leq \beta_{(l')} + \beta_{(l'-1)}. \quad (32)$$

Then, the outage probability P_l can be bounded as follows:

$$P_l^{lb} \leq P_l \leq P_l^{ub}, \quad \text{where}$$
$$P_l^{lb} = 1 - \bar{P}_l^{lb} = P\left\{\gamma_{lb} \leq \frac{\eta}{\rho}\right\} = F_{\gamma_{lb}}\left(\frac{\eta}{\rho}\right),$$
$$P_l^{ub} = 1 - \bar{P}_l^{ub} = P\left\{\gamma_{ub} \leq \frac{\eta}{\rho}\right\} = F_{\gamma_{ub}}\left(\frac{\eta}{\rho}\right), \quad (33)$$

where $\gamma_{lb} = \beta_{(l')} + \beta_{(l'-1)}$ and $\gamma_{ub} = \gamma_{(l)} + \gamma_{(l-1)}$. The following lemma provides the closed-form expressions for the cumulative distribution functions (CDFs) of γ_{lb} and γ_{ub}.

Lemma 1: When all the links experience i.i.d Rayleigh fading, the CDFs of γ_{lb} and γ_{ub} can be respectively given by

$$F_{\gamma_{lb}}(z) = \frac{2l!}{(l-2)!}\left(\sum_{k=2}^{2l-3}\binom{2l-3}{k}(-1)^k Q_2 + Q_1 + Q_0\right), \quad (34)$$

$$F_{\gamma_{ub}}(z) = \frac{l!}{(l-2)!}\sum_{k=1}^{l-2}\binom{l-2}{k}\frac{(-1)^k}{k(k+2)}J_1 + J_0, \quad (35)$$

where

$$Q_2 = \frac{e^{-2z}}{k-1}\left(1 - e^{-\frac{k-1}{2}z}\right) - \frac{2e^{-z}}{k}\left(1 - e^{-\frac{k}{2}z}\right) + \frac{2}{k+2}\left(1 - e^{-\frac{k+2}{2}z}\right) - \frac{1}{k+3}\left(1 - e^{-\frac{k+3}{2}z}\right),$$
$$Q_1 = (2l-3)\left(2e^{-z} - \frac{4}{3}e^{-\frac{3}{2}z} - \left(\frac{z}{2} + \frac{1}{4}\right)e^{-2z} - \frac{1}{2}\right),$$
$$Q_0 = \frac{4}{3}e^{-\frac{3}{2}z} - (z+1)e^{-z} - e^{-2z} + \frac{2}{3},$$
$$J_1 = k + 2e^{-(k+2)z} - (k+2)e^{-2z},$$
$$J_0 = \frac{l!}{2(l-2)!}\left(1 - e^{-2z} - 2ze^{-2z}\right).$$

Proof: See Appendix A.

The probability of the event that a relay is randomly selected from S_r can be written as:

$$P\left\{\log_2\left(1 + \frac{\alpha_1^2|g_n|^2}{\alpha_2^2|g_n|^2 + 1/\rho}\right) \geq R_1, \log_2\left(1 + \rho\alpha_2^2|g_n|^2\right) \geq R_2\right\}$$
$$= P\left\{|g_n|^2 \geq \eta/\rho\right\} = e^{-\frac{\eta}{\rho}}, \quad (36)$$

while the probability to have l available relays in S_r is:

$$P(|S_r| = l) = \binom{N}{l}e^{-\frac{\eta}{\rho}l}\left(1 - e^{-\frac{\eta}{\rho}}\right)^{N-l}. \quad (37)$$

Using (29), (33), (34), (35) and (37) into (28), and after some manipulations, the lower and upper bounds of the system outage probability for DRS-FPA scheme can be obtained in the following theorem.

Theorem 1: The lower and upper bounds on the outage probability for the two-stage DRS-FPA scheme can be respectively expressed as follows:

$$P_{\text{out}}^{lb} = \left(1-e^{-\frac{\eta}{\rho}}\right)^N + Ne^{-\frac{\eta}{\rho}}\left(1-e^{-\frac{\eta}{\rho}}\right)^{N-1}\left(1-e^{-\frac{a}{\rho}}\right) + \sum_{l=2}^{N}\binom{N}{l}e^{-\frac{\eta}{\rho}l}\left(1-e^{-\frac{\eta}{\rho}}\right)^{N-l}F_{\gamma_{lb}}\left(\frac{\eta}{\rho}\right), \tag{38}$$

$$P_{\text{out}}^{ub} = \left(1-e^{-\frac{\eta}{\rho}}\right)^N + Ne^{-\frac{\eta}{\rho}}\left(1-e^{-\frac{\eta}{\rho}}\right)^{N-1}\left(1-e^{-\frac{a}{\rho}}\right) + \sum_{l=2}^{N}\binom{N}{l}e^{-\frac{\eta}{\rho}l}\left(1-e^{-\frac{\eta}{\rho}}\right)^{N-l}F_{\gamma_{ub}}\left(\frac{\eta}{\rho}\right). \tag{39}$$

At high SNRs, the lower and upper bounds of the outage probability can be approximated as:

$$P_{\text{out}}^{lb} \approx \frac{1}{\rho^N}\left(\eta^N + Na\eta^{N-1}\right) + \sum_{l=2}^{N}\frac{\eta^{N+l}}{\rho^{N+l}}\binom{N}{l}2^{-2l}, \tag{40}$$

$$P_{\text{out}}^{ub} \approx \frac{1}{\rho^N}\left(\eta^N + Na\eta^{N-1} + \eta^N\sum_{l=2}^{N}\binom{N}{l}2^l\right). \tag{41}$$

Proof: See Appendix B.

From (40) and (41), we can conclude that the two-stage DRS-FPA scheme can achieve a full diversity order of N.

For the SRS-DPA and DRS-DPA schemes, based on (26) and (27), the condition coverage probability for the SRS-DPA scheme of $|S_r| = k \geq 1$ and the DRS-DPA scheme of $|S_r| = 1$ and $|S_r| = l \geq 2$ can be obtained as follows, respectively

$$\begin{aligned}\bar{P}_k^{\text{SRS}} &= P\left\{\frac{1}{2}\log_2\left(1+\alpha_2\rho|h_{n^*2}|^2 \geq R_2\Big||S_r| = k\right)\right\},\\ \bar{P}_1^{\text{DRS}} &= P\left\{\frac{1}{2}\log_2\left(1+\alpha_2\rho|h_{(N)2}|^2 \geq R_2\Big||S_r| = 1\right)\right\},\\ \bar{P}_l^{\text{DRS}} &= P\left\{\frac{1}{2}\log_2\left(1+\alpha_2\rho\gamma_{\text{sum}} \geq R_2\Big||S_r| = l\right)\right\}.\end{aligned} \tag{42}$$

Following the steps shown in Appendix C, the exact expressions for the system outage probabilities achieved by the two-stage SRS-DPA and DRS-DPA schemes can be presented in the following theorem.

Theorem 2: The outage probabilities of the two-stage SRS-DPA and DRS-DPA schemes for cooperative NOMA can be obtained as follows:

$$P_{\text{out}}^{\text{SRS}} = (1-q)^N + \sum_{l=1}^{N}\binom{N}{l}q^{l-1}(1-q)^{N-l} \times \left(e^{-\frac{2a_2}{\rho}}\left(1-e^{-\frac{a_2}{\rho}}\right)^l + f_1\right), \tag{43}$$

$$P_{\text{out}}^{\text{DRS}} = (1-q)^N + Nq(1-q)^N + \sum_{l=2}^{N}\binom{N}{l}q^{l-2}(1-q)^{N-l} \times (c+f_2)(2q-c-f_2). \tag{44}$$

where

$$\begin{aligned}q &= \int_{\frac{a_2}{\rho}}^{\infty} e^{-\frac{\epsilon_1 x}{\rho x - a_1}}e^{-x}dx,\\ c &= e^{-\frac{2a_2}{\rho}}F_{\gamma_{\text{sum}}}\left(\frac{a_2}{\rho}\right),\\ f_1 &= \int_{\frac{a_2}{\rho}}^{\infty}\int_{\frac{a_2}{\rho}}^{y}\frac{\epsilon_1 a_1}{(\rho z - a_1)^2}e^{-\frac{\epsilon_1 z}{\rho z - a_1}}(1-e^{-z})^l e^{-y}dzdy,\\ f_2 &= \int_{\frac{a_2}{\rho}}^{\infty}\int_{\frac{a_2}{\rho}}^{y}\frac{\epsilon_1 a_1}{(\rho z - a_1)^2}e^{-\frac{\epsilon_1 z}{\rho z - a_1}}F_{\gamma_{\text{sum}}}(z)e^{-y}dzdy,\\ F_{\gamma_{\text{sum}}}(z) &= l(l-1)\sum_{k=1}^{l-2}\binom{l-2}{k}(-1)^k\left(\frac{1}{k+2}-\frac{1}{k}e^{-z} + \frac{2}{k(k+2)}e^{-\frac{k+2}{2}z}\right) + \frac{l(l-1)}{2}\left(1-e^{-z}-ze^{-z}\right).\end{aligned}$$

Proof: See Appendix C.

In the high SNR region, $\rho \to \infty$, and $P_{\text{out}}^{\text{SRS}}$ can be approximated as follows:

$$P_{\text{out}}^{\text{SRS}} \approx \frac{1}{\rho^N}\left(b^N + \sum_{l=1}^{N}\binom{N}{l}b^{N-l}a_2^l\right) + \frac{1}{\rho^{N+1}}\sum_{l=1}^{N}\binom{N}{l}\frac{\pi}{2N}\sum_{i=1}^{N}\left|\sin\frac{2i-1}{N}\right|\left(\frac{\epsilon_1}{s_i}+a_1\right)^l, \tag{45}$$

where $b = a_2 + \epsilon_1$. Similarly, the lower and upper approximations on $P_{\text{out}}^{\text{DRS}}$ can be respectively expressed as follows:

$$P_{\text{lb}}^{\text{DRS}} \approx \frac{1}{\rho^N}\left(b^N + Nb^N + 2\sum_{l=2}^{N}\binom{N}{l}b^{N-l}\frac{a_2^l}{2^l}\right) + \frac{1}{\rho^{N+1}}\sum_{l=2}^{N}\binom{N}{l}\frac{\pi}{2^l N}\sum_{i=1}^{N}\left|\sin\frac{2i-1}{N}\right|\left(\frac{\epsilon_1}{s_i}+a_1\right)^l, \tag{46}$$

$$P_{\text{ub}}^{\text{DRS}} \approx \frac{1}{\rho^N}\left(b^N + Nb^N + 2\sum_{l=2}^{N}\binom{N}{l}b^{N-l}a_2^l\right) + \frac{1}{\rho^{N+1}}\sum_{l=2}^{N}\binom{N}{l}\frac{\pi}{N}\sum_{i=1}^{N}\left|\sin\frac{2i-1}{N}\right|\left(\frac{\epsilon_1}{s_i}+a_1\right)^l, \tag{47}$$

Proof: See Appendix C.

It can be seen easily form (45), (46) and (47) that full diversity gain can be achieved by cooperative NOMA with both two-stage DF SRS-DPA and DRS-DPA schemes.

Note that the proposed two-stage DF DRS schemes including DRS-FPA and DRS-DPA could yield better outage performance than the existing SRS-FPA [9] and SRS-half-DPA [10] schemes. Meanwhile, all the schemes can achieve

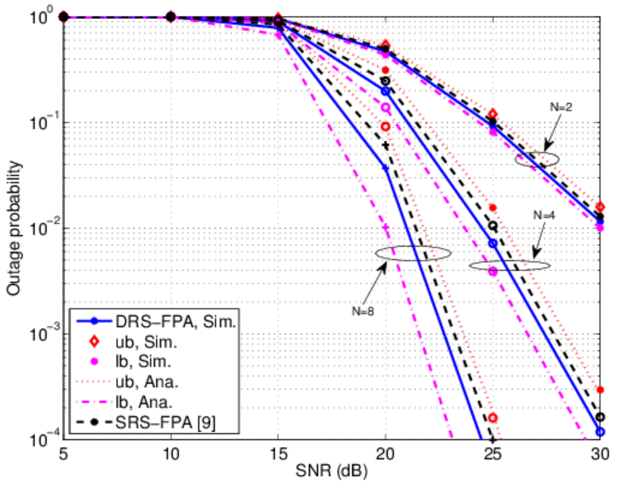

FIGURE 2. Impact of the relay numbers N on the outage performance of the two-stage DF DRS-FPA scheme with space time coding for cooperative NOMA, where $R_1 = 0.5$bits/s/Hz, $R_2 = 2$bits/s/Hz, the power allocation factor $\alpha_1^2 = \frac{3}{4}$ [9], where lb denotes lower bound and ub denotes upper bound.

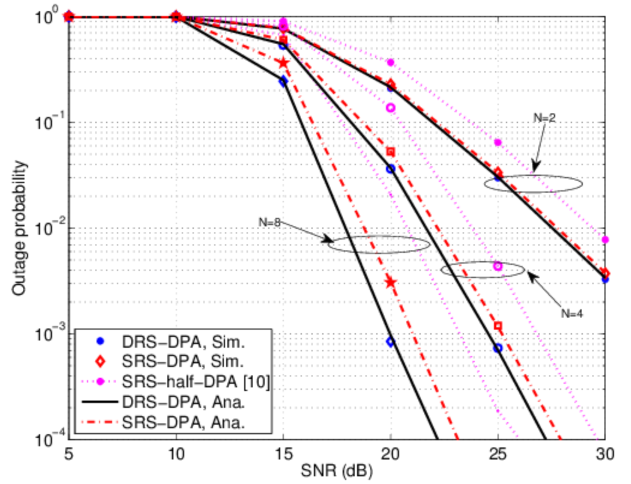

FIGURE 4. Impact of the relay numbers N on the outage performance of the two-stage DF DRS-DPA scheme with space time coding and the two-stage DF SRS-DPA shceme for cooperative NOMA, where $R_1 = 0.5$bits/s/Hz, $R_2 = 2$bits/s/Hz and for comparison, the power allocation coefficient of SRS-half-DPA scheme $\gamma_1 = \frac{3}{4}$ [10].

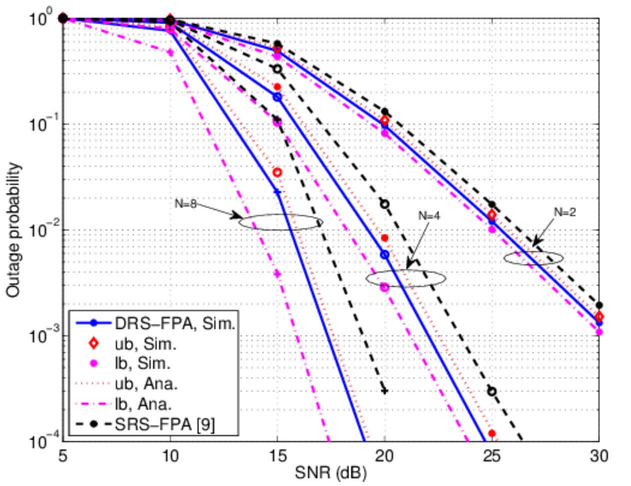

FIGURE 3. Outage performance of the two-stage DF DRS-FPA scheme with space time coding for cooperative NOMA, where $R_1 = 1$bits/s/Hz, $R_2 = 1$bits/s/Hz, the power allocation factor $\alpha_1^2 = \frac{4}{5}$ under the different relay numbers N.

the full diversity order. In addition, the DRS-DPA strategy outperforms the DRS-FPA strategy due to its ability to adjust the power allocation factors dynamically.

IV. NUMERICAL AND SIMULATION RESULTS

In this section, the outage performance of the proposed two-stage DRS-FPA, SRS-DPA and DRS-DPA schemes for cooperative NOMA network with space time coding is evaluated by using computer simulations.

Figs. 2 and 3 show the outage probability for the two-stage DF relaying with the DRS-FPA scheme at the target data rates $R_1 = 0.5$ bits/s/Hz, $R_2 = 2$ bits/s/Hz, the power allocation factor $\alpha_1^2 = \frac{3}{4}$ and $R_1 = 1$ bits/s/Hz, $R_2 = 1$ bits/s/Hz, $\alpha_1^2 = \frac{4}{5}$, respectively. It can be seen from both figures that the proposed two-stage DF DRS-FPA scheme can remarkably enhance the outage performance compared to the two-stage DF SRS-FPA scheme [9]. Furthermore, by reducing the gap between R_1 and R_2 as well as by increasing the number of the relays, the outage performance gap between the two relay selection schemes becomes significantly larger. In addition, both lower and upper bounds projected in Theorem 1 match the Monte Carlo simulations for all the SNR values. Furthermore, the upper bound becomes tighter, when there are more relays.

In Fig. 4, the outage performance of the two-stage DF SRS-DPA and DRS-DPA schemes with space time coding is compared to the two-stage DF SRS-half-DPA scheme [10] for cooperative NOMA, where the target data rates $R_1 = 0.5$ bits/s/Hz and $R_2 = 2$ bits/s/Hz. Note that both SRS-DPA and DRS-DPA schemes significantly outperform the SRS-half-DPA scheme for all the SNR values, while all of them can achieve the same diversity gain. It is worth mentioning that, as the number of relays N increases, the gain achieved by the DRS-DPA scheme is more obvious compared to the SRS-DPA scheme and SRS-half-DPA scheme, i.e. when the relay number $N = 8$, the gap between DRS-DPA scheme and SRS-DPA scheme is 1dB, while the DRS-DPA scheme realizes about 3.5dB gain over the SRS-half-DPA scheme at $P_{\text{out}} = 10^{-3}$. In addition, one can observe that the simulation results perfectly match the analytical ones, which are based on Theorem 2 for the SRS/DRS-DPA schemes. This clearly demonstrates the correctness of the developed analysis.

In Fig. 5, we compare the outage performance for the two-stage DF DRS-FPA and DRS-DPA schemes with space time coding for cooperative NOMA network. It can be evidently seen that the DRS-DPA scheme can obtain much better outage performance than DRS-FPA. The main reason for this is that the cooperative NOMA network is sensitive to the relation between the target data rates and power allocation

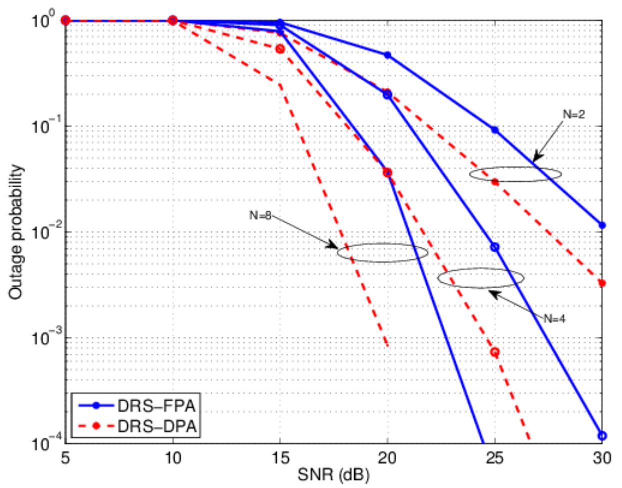

FIGURE 5. Outage performance comparison between the two-stage DF DRS-FPA and DRS-DPA schemes with space time coding for cooperative NOMA, where $R_1 = 0.5$bits/s/Hz, $R_2 = 2$bits/s/Hz, the power allocation factor $\alpha_1^2 = \frac{3}{4}$ with different relay numbers N.

factors. Therefore, fixed power allocation can always lead the system in outage, if a wrong choice is used for the power allocation coefficients, while in the DRS-DPA scheme, one can adjust the values of the power allocation factors dynamically according to the channel gains and the user's target data rates, which is more flexible.

V. CONCLUSIONS

In this paper, we have proposed two kinds of two-stage DF dual relay selection schemes with distributed space time coding for cooperative NOMA, i.e., the DRS-FPA scheme and DRS-DPA scheme. Closed-form lower and upper bounds and exact analytical expressions of the outage probabilities for DRS-FPA and DRS-DPA schemes were derived, respectively. The developed analytical results match those obtained from simulations well and it is pointed out that all the dual relay selection schemes outperform the existing single relay selection schemes, as well as achieve full diversity gain. Furthermore, the impact of the relay number and the users' target data rates on the performance was discussed, and the gain achieved by the DRS scheme is more obvious with more relays. Besides, the outage performance of the DRS-DPA scheme is superior to that of the DRS-FPA scheme, because in the DRS-DPA scheme, one can adapt the system with more flexible parameter selection. A cooperative NOMA system with more complicated fading channel model, such as Nakagami-m fading channel [18] for both DF and AF relay selection schemes will be investigated as a future work.

APPENDIX A
PROOF OF LEMMA 1

Since all the links experience i.i.d Rayleigh fading, without loss of generality, it is assumed that $\sigma_{g_i}^2 = \sigma_{h_{ij}}^2 = 1$, and the CDF of $|h_{ij}|^2$ $(i = 1, \cdots, N, j = 1, 2)$ is $F(x) = 1 - e^{-x}$.

Based on the order statistics in [19], the CDF and PDF of γ_i are $F_{\gamma_i}(x) = 1 - e^{-2x}$ and $f_{\gamma_i}(x) = 2e^{-2x}$, respectively. The joint PDF of $\gamma_{(l-1)}$ and$\gamma_{(l)}$ follows that for $x \leq y$

$$\begin{aligned} f_{\gamma_{(l-1)},\gamma_{(l)}}(x,y) &= \frac{l!}{(l-2)!} f_{\gamma_i}(x) f_{\gamma_i}(y) \left[F_{\gamma_i}(x)\right]^{l-2} \\ &= \frac{l!}{(l-2)!} 2e^{-2x} 2e^{-2y} \left[1 - e^{-2x}\right]^{l-2}. \end{aligned} \tag{48}$$

The CDF of γ_{ub} can be obtain by

$$\begin{aligned} F_{\gamma_{ub}}(z) &= F_{\gamma_{(l-1)}+\gamma_l}(z) \\ &= \int_0^{z/2} \int_x^{z-x} f_{\gamma_{(l-1)},\gamma_{(l)}}(x,y)\, dxdy \\ &= \frac{2l!}{(l-2)!} \sum_{k=0}^{l-2} \binom{l-2}{k} (-1)^k \\ &\quad \times \int_0^{z/2} \left(e^{-2(k+2)x} - e^{-2z} e^{-2kx}\right) dx. \end{aligned} \tag{49}$$

Similarly, the CDF and PDF of β_i are $F_{\beta_i}(x) = \left(1 - e^{-x}\right)^2$ and $f_{\beta_i}(x) = 2e^{-x}\left(1 - e^{-x}\right)$, respectively. The joint PDF of $\beta_{(l'-1)}$ and$\beta_{(l')}$ follows that for $x \leq y$

$$\begin{aligned} f_{\beta_{(l'-1)},\beta_{(l')}}(x,y) &= \frac{l!}{(l-2)!} f_{\beta_i}(x) f_{\beta_i}(y) \left[F_{\beta_i}(x)\right]^{l-2} \\ &= \frac{l!}{(l-2)!} 2e^{-x}\left(1 - e^{-x}\right) 2e^{-y}\left(1 - e^{-y}\right) \\ &\quad \times \left[\left(1 - e^{-x}\right)^2\right]^{l-2}. \end{aligned} \tag{50}$$

The CDF of γ_{lb} can be obtain by

$$\begin{aligned} F_{\gamma_{lb}}(z) &= F_{\beta_{(l'-1)}+\beta_{(l')}}(z) \\ &= \int_0^{z/2} \int_x^{z-x} f_{\beta_{(l'-1)},\beta_{(l')}}(x,y)\, dxdy \\ &= \int_0^{z/2} \frac{l!}{(l-2)!} 2e^{-x}\left(1 - e^{-x}\right)^{2l-3} \\ &\quad \times \left(e^{-2(z-x)} - 2e^{-(z-x)} - e^{-2x} + 2e^{-x}\right) dx \\ &= \frac{2l!}{(l-2)!} \int_0^{z/2} \sum_{k=0}^{2l-3} \binom{2l-3}{k} (-1)^k \\ &\quad \times \Big(e^{-2z} e^{-(k-1)x} - 2e^{-z} e^{-kx} - e^{-(k+3)x} \\ &\quad + 2e^{-(k+2)x}\Big)\, dx. \end{aligned} \tag{51}$$

After some computations for (49)) and (51), the CDFs for the lower and upper bounds can be expressed as $F_{\gamma_{lb}}(z)$ and $F_{\gamma_{lb}}(z)$ in (34) and (35), respectively.

APPENDIX B
PROOF OF THEOREM 1

The diversity orders of the lower and upper bounds of the outage probability will be discussed in the following part. In order to analyze the problems easily, (31) and (32) can be written as follows.

$$\gamma_{lb} = \beta_{(l')} + \beta_{(l'-1)} < 2\beta_{(l')}, \tag{52}$$

$$\gamma_{ub} = \gamma_{(l)} + \gamma_{(l-1)} > \gamma_{(l)}, \tag{53}$$

Then it is noted that,

$$P\left(\gamma_{lb}<z\right)>P\left(2\beta_{(l')}<z\right)\Rightarrow F_{\gamma_{lb}}\left(z\right)>F_{\beta_{(l')}}\left(\frac{z}{2}\right),$$
$$P\left(\gamma_{ub}<z\right)<P\left(\gamma_{(l)}<z\right)\Rightarrow F_{\gamma_{ub}}\left(z\right)<F_{\gamma_{(l)}}\left(z\right),$$

where,

$$F_{\beta_{(l')}}\left(\frac{z}{2}\right)=\left(1-e^{-\frac{z}{2}}\right)^{2l},$$
$$F_{\gamma_{(l)}}\left(z\right)=\left(1-e^{-2z}\right)^{l}.$$

At high SNR, ρ approaches infinity, η/ρ approaches zero. When $x\to 0$, the exponential function can be approximated by applying the Taylor series as $e^{-x}\approx 1-x$. Therefore, using the fact that $F_{\beta_{(l')}}\left(\frac{z}{2}\right)\approx 2^{-2l}z^{2l}$ and $F_{\gamma_{(l)}}\left(z\right)\approx 2^{l}z^{l}$, the CDFs of the lower and upper bounds can be approximated as follows, respectively.

$$F_{\gamma_{lb}}\left(z\right)\approx 2^{-2l}z^{2l}, \tag{54}$$
$$F_{\gamma_{ub}}\left(z\right)\approx 2^{l}z^{l}, \tag{55}$$

By using (54) and (55) into (38) and (39), respectively, the diversity gain can be obtained.

APPENDIX C
PROOF OF THEOREM 2

The probabilities $\bar{P}_k^{\mathrm{SRS}}$ and $\bar{P}_l^{\mathrm{DRS}}$ in (42) can be expressed as follows, respectively

$$\bar{P}_k^{\mathrm{SRS}}=P\left\{\alpha_2\geq\frac{\epsilon_2}{\rho|h_{n^*2}|^2}\middle||S_r|=k\right\},$$
$$\bar{P}_l^{\mathrm{DRS}}=P\left\{\alpha_2\geq\frac{\epsilon_2}{\rho\gamma_{\mathrm{sum}}}\middle||S_r|=l\right\},$$

By applying (26) and (27), $\bar{P}_k^{\mathrm{SRS}}$ and $\bar{P}_l^{\mathrm{DRS}}$ can be written as

$$\bar{P}_k^{\mathrm{SRS}}=\frac{T}{q};\quad \bar{P}_l^{\mathrm{DRS}}=\frac{T_1T_2}{q_1q_2}. \tag{56}$$

and

$$\begin{aligned}
T&=P\left\{|h_{n^*2}|^2\geq\frac{a_2}{\rho},|h_{n^*1}|^2\geq g(|h_{n^*2}|^2),\right.\\
&\qquad\left.|g_{n^*}|^2\geq\frac{a_2}{\rho},|h_{n^*1}|^2\geq g(|g_{n^*}|^2)\right\},\\
q&=P\left\{|g_{n^*}|^2\geq\frac{a_2}{\rho},|h_{n^*1}|^2\geq g(|g_{n^*}|^2)\right\},\\
T_1&=P\left\{\gamma_{\mathrm{sum}}\geq\frac{a_2}{\rho},|h_{(N)1}|^2\geq g(\gamma_{\mathrm{sum}}),\right.\\
&\qquad\left.|g_{(N)}|^2\geq\frac{a_2}{\rho},|h_{(N)1}|^2\geq g(|g_{(N)}|^2)\right\},\\
T_2&=P\left\{\gamma_{\mathrm{sum}}\geq\frac{a_2}{\rho},|h_{(N-1)1}|^2\geq g(\gamma_{\mathrm{sum}}),\right.\\
&\qquad\left.|g_{(N-1)}|^2\geq\frac{a_2}{\rho},|h_{(N-1)1}|^2\geq g(|g_{(N-1)}|^2)\right\},\\
q_1&=P\left\{|g_{(N)}|^2\geq\frac{a_2}{\rho},|h_{(N)1}|^2\geq g(|g_{(N)}|^2)\right\},\\
q_2&=P\left\{|g_{(N-1)}|^2\geq\frac{a_2}{\rho},|h_{(N-1)1}|^2\geq g(|g_{(N-1)}|^2)\right\},
\end{aligned}$$

where $g(x)=\frac{\epsilon_1 x}{\rho x-a_1}$ is a decreasing function, due to the i.i.d Rayleigh fading, the terms $T_1=T_2$, $q_1=q_2=q$. Then the parameters above can be further evaluated as follows

$$q=\int_{\frac{a_2}{\rho}}^{\infty}e^{-\frac{\epsilon_1 y}{\rho y-a_1}}e^{-y}dy, \tag{57}$$

$$\begin{aligned}
T_1&=\int_{\frac{a_2}{\rho}}^{\infty}\int_{\frac{a_2}{\rho}}^{y}e^{-\frac{\epsilon_1 z}{\rho z-a_1}}f_{\gamma_{\mathrm{sum}}}(z)e^{-y}dzdy\\
&\quad+\int_{\frac{a_2}{\rho}}^{\infty}\int_{y}^{\infty}f_{\gamma_{\mathrm{sum}}}(z)e^{-\frac{\epsilon_1 y}{\rho y-a_1}}e^{-y}dzdy\\
&=\int_{\frac{a_2}{\rho}}^{\infty}e^{-\frac{\epsilon_1 y}{\rho y-a_1}}e^{-y}dy-e^{-\frac{2a_2}{\rho}}F_{\gamma_{\mathrm{sum}}}\left(\frac{a_2}{\rho}\right)\\
&\quad-\int_{\frac{a_2}{\rho}}^{\infty}\int_{\frac{a_2}{\rho}}^{y}\frac{\epsilon_1 a_1}{(\rho z-a_1)^2}e^{-\frac{\epsilon_1 z}{\rho z-a_1}}F_{\gamma_{\mathrm{sum}}}(z)e^{-y}dzdy,
\end{aligned} \tag{58}$$

$$\begin{aligned}
T&=\int_{\frac{a_2}{\rho}}^{\infty}e^{-\frac{\epsilon_1 y}{\rho y-a_1}}e^{-y}dy-e^{-\frac{2a_2}{\rho}}F_{|h_{n^*2}|^2}\left(\frac{a_2}{\rho}\right)\\
&\quad-\int_{\frac{a_2}{\rho}}^{\infty}\int_{\frac{a_2}{\rho}}^{y}\frac{\epsilon_1 a_1}{(\rho z-a_1)^2}e^{-\frac{\epsilon_1 z}{\rho z-a_1}}F_{|h_{n^*2}|^2}(z)e^{-y}dzdy,
\end{aligned} \tag{59}$$

where $F_{\gamma_{\mathrm{sum}}}(z)$ is the CDF of γ_{sum}, which can be presented as

$$\begin{aligned}
F_{\gamma_{\mathrm{sum}}}(z)&=l(l-1)\sum_{k=1}^{l-2}\binom{l-2}{k}(-1)^k\left(\frac{1}{k+2}-\frac{1}{k}e^{-z}\right.\\
&\quad\left.+\frac{2}{k(k+2)}e^{-\frac{k+2}{2}z}\right)+\frac{l(l-1)}{2}\left(1-e^{-z}-ze^{-z}\right).
\end{aligned} \tag{60}$$

and $F_{|h_{n^*2}|^2}(z)$ is the CDF of $|h_{n^*2}|^2$,

$$F_{|h_{n^*2}|^2}(z)=\left(1-e^{-z}\right)^{|S_r|}. \tag{61}$$

In the same way, the probability $\bar{P}_1$ in (42) can be calculated by

$$\bar{P}_1=\int_{\frac{a_2}{\rho}}^{\infty}e^{-\frac{\epsilon_1 y}{\rho y-a_1}}e^{-y}dy. \tag{62}$$

The probability of the event that $|S_r|=l$ can be obtained as follows

$$P\left(|S_r|=l\right)=\binom{N}{l}P_a^l\left(1-P_a\right)^{N-l}, \tag{63}$$

where

$$\begin{aligned}
P_a&=P\left(|g_n|^2\geq\frac{a_2}{\rho},|h_{n1}|^2\geq\frac{\epsilon_1|g_n|^2}{\rho|g_n|^2-a_1}\right)\\
&=\int_{\frac{a_2}{\rho}}^{\infty}e^{-\frac{\epsilon_1 x}{\rho x-a_1}}e^{-x}dx.
\end{aligned}$$

Then Theorem 2 is proved by substituting the corresponding terms into (28).

As $\gamma_{\mathrm{sum}}=|h_{(N)2}|^2+|h_{(N-1)2}|^2$, it is easily found that $|h_{(N)2}|^2<\gamma_{\mathrm{sum}}<2|h_{(N)2}|^2$, then $F_{|h_{(N)2}|^2}(z)>F_{\gamma_{\mathrm{sum}}}(z)>$

$F_{|h_{(N)2}|^2}\left(\frac{z}{2}\right)$, where $F_{|h_{(N)2}|^2}(z) = (1-e^{-x})^l$. Therefore, the lower and upper bounds on T_1 can be presented as follows:

$$\begin{aligned} T_1^{lb} &= \int_{\frac{a_2}{\rho}}^{\infty} e^{-\frac{\epsilon_1 y}{\rho y - a_1}} e^{-y} dy - e^{-\frac{2a_2}{\rho}} (1-e^{-\left(\frac{a_2}{\rho}\right)})^l \\ &\quad - \int_{\frac{a_2}{\rho}}^{\infty} \int_{\frac{a_2}{\rho}}^{y} \frac{\epsilon_1 a_1}{(\rho z - a_1)^2} e^{-\frac{\epsilon_1 z}{\rho z - a_1}} (1-e^{-z})^l e^{-y} dz dy \\ &= q - e^{-\frac{2a_2}{\rho}} (1-e^{-\left(\frac{a_2}{\rho}\right)})^l - f_1, \end{aligned} \tag{64}$$

$$\begin{aligned} T_1^{ub} &= \int_{\frac{a_2}{\rho}}^{\infty} e^{-\frac{\epsilon_1 y}{\rho y - a_1}} e^{-y} dy - e^{-\frac{2a_2}{\rho}} (1-e^{-\left(\frac{a_2}{2\rho}\right)})^l \\ &\quad - \int_{\frac{a_2}{\rho}}^{\infty} \int_{\frac{a_2}{\rho}}^{y} \frac{\epsilon_1 a_1}{(\rho z - a_1)^2} e^{-\frac{\epsilon_1 z}{\rho z - a_1}} (1-e^{-\frac{z}{2}})^l e^{-y} dz dy \\ &= q - e^{-\frac{2a_2}{\rho}} (1-e^{-\left(\frac{a_2}{2\rho}\right)})^l - g_1. \end{aligned} \tag{65}$$

Assume $\rho \to \infty$ in the following part. Let $t = \frac{\rho y - a_1}{\epsilon_1}$, and the above q can be expressed as follows:

$$\begin{aligned} q &= \frac{\epsilon_1}{\rho} e^{-\frac{a_2}{\rho}} \int_1^{\infty} e^{-\frac{a_1}{\rho t}} e^{-\frac{\epsilon_1 t}{\rho}} dt \\ &= \frac{\epsilon_1}{\rho} e^{-\frac{a_2}{\rho}} \left(\int_0^{\infty} e^{-\frac{a_1}{\rho t} - \frac{\epsilon_1 t}{\rho}} dt - \int_0^1 e^{-\frac{a_1}{\rho t} - \frac{\epsilon_1 t}{\rho}} dt \right), \end{aligned} \tag{66}$$

By using $\int_0^{\infty} e^{-\frac{\beta}{4x} - \gamma x} dx = \sqrt{\frac{\beta}{\gamma}} K_1(\sqrt{\beta\gamma})$ in [20], the first term in q can be calculated as follows

$$\int_0^{\infty} e^{-\frac{a_1}{\rho t} - \frac{\epsilon_1 t}{\rho}} dt = \sqrt{\frac{4a_1}{\epsilon_1}} K_1(\sqrt{\frac{4a_1\epsilon_1}{\rho^2}}), \tag{67}$$

Similar to [10], the Gauss-Chebyshev integral is applied to approximate the second integral in q,

$$\int_0^1 e^{-\frac{a_1}{\rho t} - \frac{\epsilon_1 t}{\rho}} dt \approx \frac{\pi}{2N} \sum_{i=1}^{N} \left| \sin \frac{2i-1}{N} \right| e^{-\frac{a_1}{\rho t} - \frac{\epsilon_1 t}{\rho}}, \tag{68}$$

where N is the Gauss-Chebyshev integral approximated sum term. Based on the approximation of the Bessel function $zK_1(z) \approx 1 + \frac{z^2}{2} ln\frac{z}{2}$, $z \to 0$ in [10], when $\rho \to \infty$, q can be approximated as follows:

$$\begin{aligned} q &\approx \frac{\epsilon_1}{\rho} e^{-\frac{a_2}{\rho}} \left(\frac{\rho}{\epsilon_1} \left(1 + \frac{a_1\epsilon_1}{\rho^2} \ln \frac{a_1\epsilon_1}{\rho^2} \right) \right. \\ &\quad \left. -1 + \frac{1}{\rho} \frac{\pi}{2N} \sum_{i=1}^{N} \left| \sin \frac{2i-1}{N} \right| \left(\frac{a_1}{t} + \epsilon_1 t \right) \right) \\ &\approx 1 - \frac{a_2 + \epsilon_1}{\rho}. \end{aligned} \tag{69}$$

Let $s = \frac{\epsilon_1}{\rho z - a_1}$, and then we can obtain the following

$$\begin{aligned} f_{11} &= \int_{\frac{a_2}{\rho}}^{y} \frac{\epsilon_1 a_1}{(\rho z - a_1)^2} e^{-\frac{\epsilon_1 z}{\rho z - a_1}} (1-e^{-z})^l dz \\ &= \frac{a_1}{\rho} e^{-\frac{\epsilon_1}{\rho}} \int_{\frac{\epsilon_1}{\rho y - a_1}}^{1} e^{-\frac{a_1 s}{\rho}} \left(1 - e^{-\frac{1}{\rho}(\frac{\epsilon_1}{s} + a_1)}\right)^l ds, \end{aligned} \tag{70}$$

As $\rho \to \infty$, combining with Gauss-Chebyshev integral, the double integral f_1 in (64) can be further evaluated as follows:

$$\begin{aligned} &\int_{\frac{a_2}{\rho}}^{\infty} \frac{a_1}{\rho} e^{-\frac{\epsilon_1}{\rho}} \int_0^1 e^{-\frac{a_1 s}{\rho}} \left(1 - e^{-\frac{1}{\rho}(\frac{\epsilon_1}{s} + a_1)}\right)^l ds e^{-y} dy \\ &= \frac{a_1}{\rho} e^{-\frac{\epsilon_1 + a_2}{\rho}} \int_0^1 e^{-\frac{a_1 s}{\rho}} \left(1 - e^{-\frac{1}{\rho}(\frac{\epsilon_1}{s} + a_1)}\right)^l ds \\ &\approx \frac{a_1}{\rho^{l+1}} \frac{\pi}{2N} \sum_{i=1}^{N} \left| \sin \frac{2i-1}{N} \right| \left(\frac{\epsilon_1}{s_i} + a_1 \right)^l. \end{aligned} \tag{71}$$

Similarly, the third term g_1 in (65) can be approximated as

$$g_1 \approx \frac{a_1}{\rho^{l+1}} \frac{\pi}{2^{l+1}N} \sum_{i=1}^{N} \left| \sin \frac{2i-1}{N} \right| \left(\frac{\epsilon_1}{s_i} + a_1 \right)^l. \tag{72}$$

where $s_i = \frac{1}{2}\left(1 + \cos \frac{2i-1}{N}\right)$ [10]. At high SNR, substituting (69), (71) and (72) into (43) and (44), respectively, the approximations for the outage probabilities of the SRS-DPA and DRS-DPA schemes are obtained.

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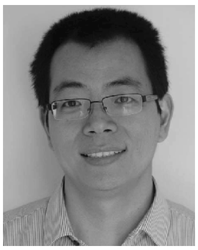

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