

On the Diversity of Network-Coded Cooperation With Decode-and-Forward Relay Selection

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Abstract—In this paper, we study outage probability (OP) and diversity order of a M -source and N -relay wireless network that combines network coding (NC) and relay selection (RS). More specifically, a decode-and-forward (DF) relaying protocol is considered and the network-encoding vectors at the relays are assumed to constitute a maximum distance separable (MDS) code. Single relay selection (SRS) and multiple relay selection (MRS) protocols are investigated, where the best relay and the L best relays forward the network-coded packets to the destination, respectively. An accurate mathematical framework for computing the OP is provided and from its direct inspection the following conclusions on the achievable diversity are drawn: 1) the SRS protocol achieves diversity order equal to two regardless of M and N and 2) the MRS protocol achieves diversity order equal to $L + 1$ if $L < M$ and equal to $N + 1$ if $L \geq M$. These analytical findings are substantiated with the aid of Monte Carlo simulations, which also show that RS provides a better OP than NC based on repetition coding if $L \geq M$.

Index Terms—Network coding, cooperative networks, relay selection, outage probability, diversity order.

I. INTRODUCTION

COOPERATIVE diversity is an effective technique for increasing the coverage and for improving the performance of wireless networks [1]. In cooperative networks, idle nodes, henceforth called relays, are allowed to overhear the packets transmitted from the sources and to forward their estimates to a destination. Since multiple copies of the same signal are received at the destination, a better end-to-end reliability is, in general, obtained. If multiple relays are available in the network and a Relay Selection (RS) protocol is used, in particular, full diversity order can be achieved [2].

In cooperative networks, in general, several sources may want to send data to the same destination with the aid of the same idle nodes. If each source uses the relays in a round-robin fashion, the price to pay for achieving full diversity may be an unacceptable reduction of the spectral efficiency [3]. To

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overcome this limitation, Network-Coded Cooperation (NCC) has recently been introduced, where the relays are capable of retransmitting all the packets received from the sources in a single time-slot, by capitalizing on the concept of Network Coding (NC) [4]. Recently, several researchers have investigated the benefits of NC for application to relay-aided networks. In [5], the capacity region of NCC is derived and it is proved that NCC is capable of outperforming classical cooperative networks. In [6] and [7], the advantages of combining NC with Single Relay Selection (SRS) and Multiple Relay Selection (MRS) protocols for application to the Two-Way Relay Channel (TWRC) are investigated, respectively. In [7], a suboptimal RS criterion for application to the TWRC with Amplify-and-Forward (AF) is introduced and studied. A similar RS protocol is considered in [8], where Outage Probability (OP), Bit Error Rate (BER) and diversity order are studied. These papers, however, are focused on the analysis of bidirectional networks. The analysis of NCC with RS for application to unidirectional networks has, on the other hand, received less attention [9], [10].

Motivated by these considerations, we study the OP and the diversity order of NCC with RS in a multiple-access relay-aided network that consists of M sources, N relays, and one destination. The considered system model may find application in the uplink of cellular networks, where a base station acts as the destination, some active mobile terminals act as the sources, and some idle mobile terminals act as the relays. This network setup has recently been investigated by other researchers. In [11], the Diversity Multiplexing Tradeoff (DMT) of NCC is studied and it is shown that full diversity can be achieved by using RS, under the assumption that the destination is able to successfully decode the packets of all the sources. In [12], the analysis in [11] is generalized by removing the above-mentioned assumption and by studying SRS and MRS protocols. The correlation of the ordered statistics originating from the RS protocol is, however, not completely taken into account [7]. In [13]–[15], the authors study OP, BER, and diversity order of Analog Network Coding (ANC). In the present paper, on the other hand, we focus our attention on the analysis of OP and diversity order of Decode-and-Forward (DF-) based RS that uses Digital NC (DNC), where the network-encoding vectors at the relays are assumed to constitute a Maximum Distance Separable (MDS) code [10]. More specifically, the present paper provides the following contributions:

- Exact and asymptotic expressions of the OP for SRS and MRS protocols are derived, which highlight fundamental performance trends as a function of several system parameters.

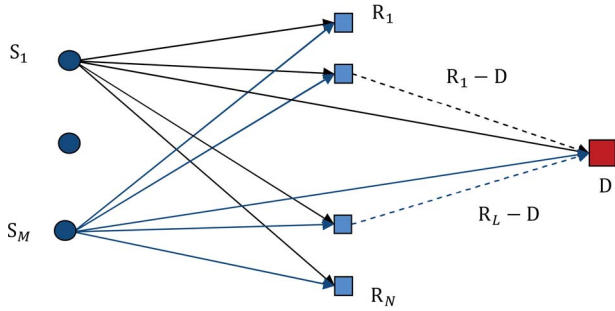


Fig. 1. M -source and N -relay wireless network combining NC and RS.

- From the asymptotic expression of the OP, the diversity order is obtained and the following conclusions are drawn: 1) the SRS protocol achieves a diversity order equal to two regardless of M and N and 2) the MRS protocol achieves a diversity order equal to $L + 1$ if $L < M$ and equal to $N + 1$ if $L \geq M$. Numerical results show that NCC with RS provides better performance than NCC with repetition-based transmission if $L \geq M$.

The remainder of the present paper is organized as follows. In Section II, the system model is introduced. In Section III, SRS and MRS protocols are described. In Section IV and Section V, the OP of SRS and MRS protocols is computed, respectively. In Section VI, the benefits of NCC with RS compared to NCC with repetition-based relaying are investigated. In Section VII, mathematical framework and findings are validated with the aid of Monte Carlo simulations. Finally, Section VIII concludes the present paper.

II. SYSTEM MODEL

We consider a cooperative network that consists of M sources denoted by S_m , $1 \leq m \leq M$, N relays denoted by R_n , $1 \leq n \leq N$, and one destination denoted by D , as depicted in Fig. 1. Perfect time synchronization is assumed and all channels experience block Rayleigh fading and Additive White Gaussian Noise (AWGN). All nodes are equipped with a single antenna and operate in a half-duplex mode. One cooperative period consists of two phases: broadcasting and relaying.

In the broadcasting phase, the sources transmit their data symbols to the relays and to the destination in non-overlapping time-slots. This phase, thus, lasts M time-slots. Let b_m denote the data symbol emitted by source S_m , $1 \leq m \leq M$. Each b_m symbol contains q data bits. A 2^q -order modulator maps b_m into a signal symbol x_m . The signal received at relay R_n , $1 \leq n \leq N$, and at the destination can be formulated as follows:

$$\begin{cases} y_{S_m R_n} = \sqrt{P_{S_m R_n}} h_{S_m R_n} x_m + z_{S_m R_n} \\ y_{S_m D} = \sqrt{P_{S_m D}} h_{S_m D} x_m + z_{S_m D} \end{cases}, \quad (1)$$

where h_{XY} for $X \in \{S_m\}$ and $Y \in \{R_n, D\}$ denotes the channel fading coefficient of the link $X \rightarrow Y$, which is a complex Gaussian random variable with zero mean and unit variance, i.e., $\mathbb{E}\{|h_{XY}|^2\} = 1$. All channels are assumed to be mutually independent; P_{XY} denotes the average received signal power at

node Y from node X , including the path loss; and $z_{(\cdot)}$ denotes the AWGN with zero mean and variance σ^2 .

The relaying phase is based on the RS protocol and it is described in the next section. Let us assume that $L \leq M$ relays are selected for relaying the data of the sources to the destination. These selected relays execute the following operations. First, they decode the data received from the sources by using a Maximum Likelihood (ML) detector as follows:

$$\hat{b}_{S_m R_n} = \arg \max_{\tilde{b}_m} \Pr\{\tilde{b}_m | y_{S_m R_n}\}, \quad (2)$$

where \tilde{b}_m denotes the hypothesis of the data symbol transmitted by source S_m .

Then, they apply NC in $\text{GF}(2^q)$ to the demodulated data and the network-coded symbol as follows is obtained:

$$\hat{b}_{R_n} = \alpha_{S_1 R_n} \hat{b}_{S_1 R_n} \boxplus \dots \boxplus \alpha_{S_M R_n} \hat{b}_{S_M R_n}, \quad (3)$$

where $\alpha_{(\cdot)}$ denotes the NC coefficients and \boxplus denotes the sum operation in $\text{GF}(2^q)$.

Finally, the network-coded symbol \hat{b}_{R_n} is modulated into a signal symbol \hat{x}_{R_n} and forwarded to the destination. Unlike [12], where only successfully decoded symbols are relayed, we assume that NC is applied to all, correct and incorrect, demodulated symbols. At the destination, this error propagation phenomenon can be mitigated by using appropriate demodulation schemes [10].

Let $\{i_1, \dots, i_L\}$ denote the indices of the selected relays. The signal received at the destination from them can be formulated as follows ($n \in \{i_1, \dots, i_L\}$):

$$y_{R_n D} = \sqrt{P_{R_n D}} h_{R_n D} \hat{x}_{R_n} + z_{R_n D}, \quad (4)$$

where $h_{R_n D}$ represents the channel fading coefficient of the link $R_n \rightarrow D$, which is a complex Gaussian random variable with zero mean and unit variance; $P_{R_n D}$ denotes the received signal power at D from R_n ; and $z_{R_n D}$ denotes the complex AWGN with zero mean and variance σ^2 .

III. RELAY SELECTION PROTOCOLS

We assume that RS is implemented based on the sub-optimal max-min selection criterion [6], which maximizes the worst end-to-end Signal-to-Noise-Ratio (SNR). In particular, two case studies are analyzed.

A. Single Relay Selection

Let us consider a generic source-to-relay-to-destination link. The end-to-end reliability of this dual-hop link is determined by the weakest link between the source-to-relay and the relay-to-destination links. Likewise, let a generic multi-source-to-relay link where NC is applied at the relays. The end-to-end reliability of this multi-point-to-point link is determined by the weakest source-to-relay link. As a result, each dual-hop multi-source-to-relay-to-destination link turns out to be equivalent to a single-hop link with the SNR as follows [10]:

$$\gamma_n = \min \{\gamma_{S_1 R_n}, \dots, \gamma_{S_M R_n}, \gamma_{R_n D}\}, \quad (5)$$

where $\gamma_{XY} \triangleq \frac{P_{XY} |h_{XY}|^2}{\sigma^2}$ denotes the instantaneous SNR of the link $X \rightarrow Y$.

Since the SNRs γ_{XY} in (5) are mutually independent and exponentially distributed (Rayleigh fading is assumed), the Cumulative Distribution Function (CDF) of γ_n can be formulated as follows [16]:

$$F_{\gamma_n}(x) = 1 - e^{-\frac{x}{\bar{\gamma}_n}}, \quad (6)$$

where

$$\frac{1}{\bar{\gamma}_n} = \frac{1}{\bar{\gamma}_{S_1R_n}} + \dots + \frac{1}{\bar{\gamma}_{S_MR_n}} + \frac{1}{\bar{\gamma}_{R_nD}} \quad (7)$$

and $\bar{\gamma}_{XY} = \frac{P_{XY}}{\sigma^2}$ denotes the average SNR of the link $X \rightarrow Y$.

In SRS, the relay with the highest equivalent SNR γ_n in (5) is selected for forwarding the data of the sources, since this maximizes the end-to-end performance. The SNR of the selected relay, denoted by g_{SRS} , can be formulated as follows:

$$g_{SRS} = \max\{\gamma_1, \dots, \gamma_N\}. \quad (8)$$

With the aid of [16], the CDF of g_{SRS} , denoted by $F_{g_{SRS}}(\cdot)$, can be formulated as follows:

$$F_{g_{SRS}}(x) = \prod_{n=1}^N F_{\gamma_n}(x) = \prod_{n=1}^N \left(1 - e^{-\frac{x}{\bar{\gamma}_n}}\right). \quad (9)$$

After the relay selection process, the selected relay forwards the network-coded symbols to the destination.

B. Multiple Relay Selection

The end-to-end reliability of SRS can be improved by allowing more than one relay to forward data of the sources to the destination. In the MRS protocol, the $1 < L \leq M$ relays with the highest SNRs in (5) are selected for data forwarding. In practice, the MRS protocol can be implemented in a distributed fashion as proposed in [2]. It is worth mentioning that the RS protocol considered in this paper is different from that used in [12], where a relay might be chosen several times.

With the aid of the same notation as for the SRS protocol, the SNRs of the L best relays can be formulated as $\mathbf{g}_{MRS} = \{g_1, \dots, g_L\}$, where $g_l = \max^l\{\gamma_1, \dots, \gamma_N\}$ denotes the l^{th} -maximum of the set $\{\gamma_1, \dots, \gamma_N\}$, which can be formally defined as follows:

$$\Pr\{g_l \leq x\} = \Pr\{(N - l + 1 \text{ values } \gamma_n \leq x) \cap (l - 1 \text{ values } \gamma_n > x)\}. \quad (10)$$

The OP of the MRS protocol depends on the distribution of \mathbf{g}_{MRS} , which in turn depends on the distribution of g_l for $l = 1, 2, \dots, L$. The following two lemmas provide the distribution of g_l , which is used in Section V for studying the end-to-end outage of MRS.

Lemma 1: The CDF, $F_{g_l}(\cdot)$, of $g_l = \max^l\{\gamma_1, \dots, \gamma_N\}$ for $1 \leq l \leq L$, where γ_n for $1 \leq n \leq N$ is defined in (5) can be formulated as follows:

$$F_{g_l}(x) = \sum_{k=1}^l (-1)^{k-1} C_{N-l+k}^{N-l+1} \Gamma_l(k, x), \quad (11)$$

where $C_k^n = \frac{n!}{(n-k)!k!}$ denotes the binomial coefficient and

$$\Gamma_l(k, x) = \sum_{\substack{i_1=1, \dots, i_{N-l+k}=1 \\ i_1 \neq \dots \neq i_{N-l+k}}}^N \prod_{n=i_1}^{i_{N-l+k}} F_{\gamma_n}(x), \quad (12)$$

as well as, for notational simplicity, the following shorthand is introduced:

$$\sum_{\substack{n \\ i_1=1, \dots, i_k=1 \\ i_1 \neq \dots \neq i_k}} \left(\prod_{j=i_1}^{i_k} x_j \right) = \sum_{i_1=1}^{n-k+1} \dots \sum_{i_k=i_{k-1}+1}^n (x_{i_1} \dots x_{i_k}) \quad (13)$$

Proof: Let $i_1, \dots, i_{N-l+1}, \dots, i_N$ denote the indices that satisfy (10), i.e., $\gamma_n < x$ for $i_1 \leq n \leq i_{N-l+1}$ and $\gamma_n > x$ for $i_{N-l+1} < n \leq i_N$. Since the SNRs γ_n are mutually independent, the probability in (10) is $\prod_{n=i_1}^{i_{N-l+1}} F_{\gamma_n}(x) \times \prod_{n'=i_{N-l+1}}^{i_N} (1 - F_{\gamma_{n'}}(x))$ and there are C_{N-l}^N combinations of indices in (10) that possibly satisfy the condition. By applying polynomial factorization of the probability of each set of indices and computing the summation, the proof follows. ■

Lemma 2: Let the SNRs be independent and identically distributed (i.i.d.), i.e., $\bar{\gamma}_1 = \dots = \bar{\gamma}_N = \bar{\gamma}$. The diversity order of g_l is $N - l + 1$.

Proof: From (11), it follows that the asymptotic behavior of the CDF of g_l depends on the terms $\Gamma_l(k, x)$, for $1 \leq k \leq l$, that decay fastest with the SNR. If the channels are i.i.d., we have $\Gamma_l(1, x) = C_{N-l+1}^N (F_{\gamma_n}(x))^{N-l+1}$. For high-SNR, we have $F_{\gamma_n}(x) \rightarrow \frac{1}{\bar{\gamma}}$, which leads to $\Gamma_l(1, x) \rightarrow C_{N-l+1}^N \frac{1}{\bar{\gamma}^{N-l+1}}$. This concludes the proof. ■

After MRS process, the L selected relays forward the network-coded symbols to the destination.

IV. OUTAGE PROBABILITY OF SRS

A. Exact Outage Probability of SRS

The mutual information of a generic single-hop link with instantaneous SNR equal to γ can be formulated as follows:

$$I(\gamma) = \log_2(1 + \gamma). \quad (14)$$

As a result, the per-link OP can be formulated as follows:

$$P_{out} = \Pr\{I < R\} = \Pr\{\gamma < \underbrace{2^R - 1}_{\gamma_{th}}\}, \quad (15)$$

where γ_{th} denotes the reliability threshold corresponding to the rate R .

As for the SRS protocol, the destination receives $M + 1$ packets: M from the sources and 1 from the best relay. An outage occurs if the destination is not able to decode the packets of all the sources, i.e., fewer than M packets are correctly decoded. In other words, the system is not in outage if there is no more than one link whose SNR is below the threshold γ_{th} . Accordingly, the OP of SRS can be formulated as

$OP_{SRS} = 1 - \overline{OP}$, where \overline{OP} is the probability that the system is not in outage, which can be written as follows:

$$\overline{OP} = \Pr\{0 \text{ links} < \gamma_{th}\} + \Pr\{1 \text{ link} < \gamma_{th}\}. \quad (16)$$

Theorem 1: Consider a cooperative network consisting of M sources, N relays, and one destination. Let NC be applied at the relays. The exact OP of SRS is as follows:

$$OP_{SRS} = 1 - \prod_{m=1}^M (1 - F_{\gamma_{S_m D}}(\gamma_{th})) + (1 - F_{g_{SRS}}(\gamma_{th})) \times \sum_{m=1}^M \left(F_{\gamma_{S_m D}}(\gamma_{th}) \prod_{m' \neq m}^M (1 - F_{\gamma_{S_{m'} D}}(\gamma_{th})) \right), \quad (17)$$

where $F_{\gamma_{S_m D}}(x) = 1 - e^{-\frac{x}{\bar{\gamma}_{S_m D}}}$, $F_{\gamma_{S_{m'} D}}(x) = 1 - e^{-\frac{x}{\bar{\gamma}_{S_{m'} D}}}$, and $F_{g_{SRS}}(\cdot)$ is given in (9).

Proof: Since the $M + 1$ channels are mutually independent, we have $\Pr\{\gamma_{S_1 D} \leq \gamma_{th}, \gamma_{SRS} \leq \gamma_{th}\} = \Pr\{\gamma_{S_1 D} \leq \gamma_{th}\} \times \Pr\{\gamma_{SRS} \leq \gamma_{th}\}$. The proof follows from (9) with the aid of some algebraic manipulations. ■

Corollary 1: Consider the same assumption as in Theorem 1. If the channels are i.i.d., i.e., $\bar{\gamma}_{S_m R_n} = \bar{\gamma}_{S_m D} = \bar{\gamma}_{R_n D} = \bar{\gamma}$, $\forall n, m$, the OP of SRS can be formulated as follows:

$$OP_{SRS}^{iid} = 1 - e^{-\frac{M\gamma_{th}}{\bar{\gamma}}} + M e^{-\frac{(M-1)\gamma_{th}}{\bar{\gamma}}} \left(1 - e^{-\frac{\gamma_{th}}{\bar{\gamma}}} \right) \times \left[1 - \left(1 - e^{-\frac{(M+1)\gamma_{th}}{\bar{\gamma}}} \right)^N \right]. \quad (18)$$

Proof: It follows directly from (17). ■

B. Asymptotic Outage Probability of SRS

The OP of SRS in Theorem 1 is a complex function of all average SNRs in the network, which does not allow one to get insightful information about the achievable diversity order. Theorem 2 provides a simpler asymptotic expression of the OP, which yields direct information on the diversity order.

Theorem 2: Consider a cooperative network consisting of M sources, N relays, and one destination. Let NC be applied at the relays. In the high-SNR regime, the asymptotic OP of SRS can be formulated as follows:

$$OP_{SRS}^{Asym} = \sum_{\substack{m=1, m'=1 \\ m \neq m'}}^M \frac{\gamma_{th}^2}{\bar{\gamma}_{S_m D} \bar{\gamma}_{S_{m'} D}}. \quad (19)$$

Proof: See Appendix A. ■

Theorem 2 highlights that the SRS protocol is capable of achieving only a diversity order equal to two regardless of the number of available relays. In particular, the asymptotic OP depends only on the source-to-destination links and it is independent of the source-to-relay and relay-to-destination links. These performance trends are different compared to their counterparts in single-source relay networks where NC is not used [2], as well as in TWRC with NC [6]. In these latter cases, in fact, full diversity order equal to N is achieved.

V. OUTAGE PROBABILITY OF MRS

In this section, we analyze the OP of the MRS protocol. We assume that the network encoding vectors employed by the L best selected relays constitute a MDS code, i.e., all encoding vectors are mutually independent [17]. As a result, the destination is capable of recovering the data of the sources after receiving at least M error-free packets, either from the sources or from the active relays.

A. Exact Outage Probability of MRS

In the MRS protocol, the destination receives $M + L$ packets: M from the sources and L from the best relays. An outage occurs if the destination is not able to decode the packets of all the sources, i.e., fewer than M packets are correctly decoded. In other words, the system is in outage if fewer than M SNRs at the destination are above the reliability threshold γ_{th} . In formulas, the OP can be written as follows:

$$OP = \Pr\{0 \text{ links} > \gamma_{th}\} + \Pr\{1 \text{ link} > \gamma_{th}\} + \dots + \Pr\{M - 1 \text{ links} > \gamma_{th}\}. \quad (20)$$

Theorem 3: Consider a cooperative network consisting of M sources, N relays, and one destination. Let NC be applied at the relays and the encoding vectors constitute a MDS code. If $L < M$, the OP of the MRS protocol can be formulated as follows:

$$OP_{MRS}^{(1)} = \left(\sum_{m=0}^{M-L-1} \Psi(m) \right) \left(1 + \sum_{l=1}^{L-1} F_{g_l}(\gamma_{th}) \right) + \sum_{k=1}^L \left(\Psi(M-k) \sum_{l=1}^k F_{g_l}(\gamma_{th}) \right), \quad (21)$$

otherwise the OP of MRS can be formulated as follows:

$$OP_{MRS}^{(2)} = \sum_{k=1}^M \left(\Psi(M-k) \sum_{l=1}^k F_{g_l}(\gamma_{th}) \right), \quad (22)$$

where $F_{g_l}(\cdot)$ is given in Lemma 1 and:

$$\Psi(k) = \sum_{\substack{i_1=1, \dots, i_k=1 \\ i_1 \neq \dots \neq i_k}}^M \left\{ \prod_{m=i_1}^{i_k} (1 - F_{\gamma_{S_m D}}(\gamma_{th})) \times \prod_{\substack{m'=1 \\ m' \neq \{i_1, \dots, i_k\}}}^M F_{\gamma_{S_{m'} D}}(\gamma_{th}) \right\}. \quad (23)$$

Proof: See Appendix B. ■

Similar to the SRS protocol, the exact OP of the MRS protocol is a complex function of all the SNRs in the network, which does not allow an easy checking of the system diversity order.

B. Asymptotic Outage Probability of MRS

Theorem 4: Consider a cooperative network consisting of M sources, N relays, and one destination. Let NC be applied at the relays and the encoding vectors constitute a MDS code. In the high-SNR regime, the asymptotic OP of the MRS protocol can be formulated as follows:

$$\text{OP}_{MRS}^{(1-Asym)} = \sum_{\substack{i_1=1, \dots, i_{L+1}=1 \\ i_1 \neq \dots \neq i_{L+1}}}^M \left(\prod_{m=i_1}^{i_{L+1}} \frac{\gamma_{th}}{\bar{\gamma}_{S_m D}} \right), \quad (24)$$

if $L < M$; otherwise, the OP is as follows:

$$\text{OP}_{MRS}^{(2-Asym)} = \sum_{k=1}^M \Omega_S(k) \Omega_R(N - k + 1), \quad (25)$$

where:

$$\Omega_S(k) = \sum_{\substack{i_1=1, \dots, i_k=1 \\ i_1 \neq \dots \neq i_k}}^M \left(\prod_{m=i_1}^{i_k} \frac{\gamma_{th}}{\bar{\gamma}_{S_m D}} \right), \quad (26)$$

and:

$$\Omega_R(k) = \sum_{\substack{i_1=1, \dots, i_k=1 \\ i_1 \neq \dots \neq i_k}}^N \left(\prod_{n=i_1}^{i_k} \frac{\gamma_{th}}{\bar{\gamma}_n} \right). \quad (27)$$

Proof: From Lemma 2, we know that $F_{g_l}(\cdot)$ has diversity order equal to $N - l + 1$. From (23), we note that $\Psi(\cdot)$ has diversity order equal to $M - k$. If $L < M$, the OP of MRS is given in (21). For high-SNR values, the first addend of (21), i.e., $\left(\sum_{m=0}^{M-L-1} \Psi(m) \right) \left(1 + \sum_{l=1}^{L-1} F_{g_l}(\gamma_{th}) \right)$, is dominated by $\Psi(M - L - 1)$. By using the approximation in (40) and by keeping the dominant elements, we obtain (24). If $L \geq M$, the OP of MRS is given in (22). For every k , $\Psi(M - k)$ and $\sum_{l=1}^k F_{g_l}(\gamma_{th})$ have a diversity order equal to k and to $N - k + 1$, respectively. Therefore, $\Omega_S(k) \Omega_R(N - k + 1)$ has diversity order equal to $N + 1$ for every k . By still applying the approximation in (40), we obtain (25). ■

Theorem 4 shows that the MRS protocol is capable of achieving a diversity order equal to $L + 1$ if $L < M$ and full diversity order equal to $N + 1$ if $L \geq M$. It is worth noting that the diversity order for $L \geq M$ is different from that obtained in [12, Theorem. 3]. The reason is that the correlation originating from the ordered statistics of the SNRs of the selected relays is ignored in [12].

Theorem 4, in addition, highlights that the asymptotic OP of the MRS protocol does not depend on the relay channels if $L < M$. This implies that the OP is independent of the number of available relays N and of their spatial locations. The relays may, for example, be randomly deployed without affecting the OP [18]. If $L \geq M$, on the other hand, the asymptotic OP depends on N , on the network topology, and on the spatial locations of the relays. In this case, selecting more relays does not improve the system performance.

If $L = 1$, Theorem 3 and Theorem 4 reduce, as expected, to Theorem 1 and to Theorem 2, respectively.

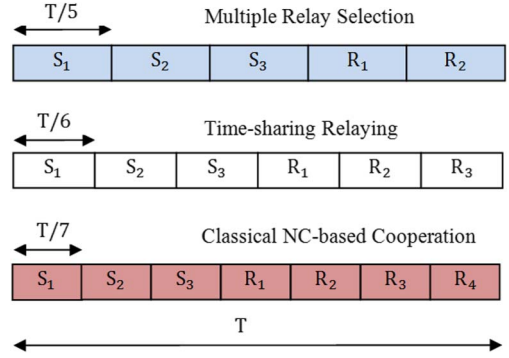


Fig. 2. Example of MRS-based NCC, time-sharing relaying and repetition-based NCC. Setup: $M = 3$, $N = 4$ and $L = 2$.

VI. COMPARISON WITH STATE-OF-THE-ART RELAYING

In this section, we compare MRS-based NCC against state-of-the-art relaying protocols, which include time-sharing relaying and NCC based on repetition coding. In particular, time-sharing relaying does not use NC and repetition-based NCC relies on all the available relays without using RS. For a fair comparison, the protocols are compared by assuming the same spectral efficiency. As example is illustrated in Fig. 2.

More specifically, let T be the total transmission time, including broadcasting and relaying. It must be the same for all protocols, to guarantee the same spectral efficiency. As a consequence, the time-slot duration is different for NCC based on MRS, time-sharing relaying, and NCC based on repetition coding. As for NCC based on MRS, the duration of a time slot is $\tau_{MRS} = T/(M + L)$. Let \mathcal{R} denote the system rate in bit per channel use. Thus, the rate in (15) for the MRS-based NCC, \mathcal{R}_{MRS} , is equal to

$$\mathcal{R}_{MRS} = \frac{\mathcal{R}}{M + L}.$$

Further details about time-sharing relaying and NCC based on repetition coding are provided in what follows.

A. Time-Sharing Relaying

In time-sharing relaying, each source relies on the help of the best available relay but NC is not applied. Consequently, the total time for completing the transmission from M sources is $2M$ time-slots.

In particular for the source S_m , the SNR of the best relay is chosen as follows [2]:

$$g_m^{TS} = \max_{n=1, \dots, N} \{ \gamma_n^{TS} \}, \quad (28)$$

where:

$$\gamma_n^{TS} = \min \{ \gamma_{S_m R_n}, \gamma_{R_n D} \}. \quad (29)$$

This implies that different sources may select different relays. The generic source S_m is in outage if both $\gamma_{S_m D}$ and g_m^{TS} are below the reliability threshold γ_{th}^{TS} . In formulas:

$$\begin{aligned} \text{OP}_m &= \Pr \{ \gamma_{S_m D} \leq \gamma_{th}^{TS}, g_m^{TS} \leq \gamma_{th}^{TS} \} \\ &= \left(1 - e^{-\frac{\gamma_{th}^{TS}}{\bar{\gamma}_{S_m D}}} \right) \prod_{n=1}^N \left(1 - e^{-\frac{\gamma_{th}^{TS}}{\bar{\gamma}_n^{TS}}} \right), \end{aligned} \quad (30)$$

where

$$\frac{1}{\bar{\gamma}_{th}^{TS}} = \frac{1}{\bar{\gamma}_{S_m R_n}} + \frac{1}{\bar{\gamma}_{R_n D}}.$$

In a multi-source network, by definition, an outage occurs if at least one source is in outage. Let $\overline{OP}_m = 1 - OP_m$ be the probability that source S_m is not in outage. The OP of time-sharing relaying can be formulated as follows:

$$OP_{TS} = 1 - \prod_{m=1}^M \overline{OP}_m = 1 - \prod_{m=1}^M (1 - OP_m), \quad (31)$$

where OP_m is given in (30).

By using the same line of thought as Theorem 2, the asymptotic (in the high-SNR regime) OP can be formulated as follows:

$$OP_{TS}^{Asymp} = \sum_{m=1}^M \left(\frac{(\bar{\gamma}_{th}^{TS})^{N+1}}{\bar{\gamma}_{S_m D}} \prod_{n=1}^N \left(\frac{1}{\bar{\gamma}_{S_m R_n}} + \frac{1}{\bar{\gamma}_{R_n D}} \right) \right). \quad (32)$$

From (32), it follows that time-sharing relaying achieves full diversity order equal to $N + 1$. Achieving full diversity order, however, does not guarantee that time-sharing relaying outperforms MRS-based NCC, since, by assuming the same spectral efficiency, the reliability thresholds of the two protocols are, in general, different, i.e., $\bar{\gamma}_{th}^{TS} \neq \gamma_{th}$. Let, in fact, the time-slot duration of time-sharing relaying be equal to $\tau_{TS} = T/(2M)$. Then, the corresponding rate is equal to $\mathcal{R}_{TS} = \mathcal{R}/(2M)$. By re-writing it in terms of $\mathcal{R}_{MRS} = \mathcal{R}/(M + L)$, we have $\mathcal{R}_{TS} = ((2M)/(M + L))\mathcal{R}_{MRS}$. As a result, $\bar{\gamma}_{th}^{TS} = 2^{\mathcal{R}_{TS}} - 1 \neq \gamma_{th} = 2^{\mathcal{R}_{MRS}} - 1$.

B. Repetition-Based (or Classical) NCC

In repetition-based NCC, all the available relays forward network-coded symbols to the destination without using RS. The destination receives $M + N$ packets at the end of broadcasting and relaying phases. Hence, the total time for completing the transmission from the M sources is $M + N$ time-slots.

In the light of the MDS assumption for the encoding vectors used at the relays, the destination is capable of retrieving the data of the M sources if it receives at least M correct packets out of the $M + N$ received ones. Let $\mathbf{g}^{CNC} = \{\gamma_{S_1 D}, \dots, \gamma_{S_M D}, \gamma_1, \dots, \gamma_N\}$ denote the vector of all the SNRs, where $\gamma_n = \min\{\gamma_{S_1 R_n}, \dots, \gamma_{S_M R_n}, \gamma_{R_n D}\}$ for $n = 1, 2, \dots, N$. The OP of repetition-based NCC can be formulated as follows:

$$OP_{CNC} = \Pr \{0 \text{ links in } \mathbf{g}^{CNC} > \bar{\gamma}_{th}^{CNC}\} + \dots + \Pr \{M - 1 \text{ links in } \mathbf{g}^{CNC} > \bar{\gamma}_{th}^{CNC}\}, \quad (33)$$

where $\bar{\gamma}_{th}^{CNC}$ denotes the reliability threshold.

By using a line of thought similar to NCC based on MRS, the OP can be formulated as follows:

$$OP_{CNC} = \sum_{k=1}^{M-1} \Psi_{CNC}(k), \quad (34)$$

where

$$\Psi_{CNC}(k) = \sum_{\substack{i_1=1, \dots, i_k=1 \\ i_1 \neq \dots \neq i_k}}^{M+N} \left[\prod_{n=i_1}^{i_k} (1 - F_{g_n^{CNC}}(\bar{\gamma}_{th}^{CNC})) \right. \\ \left. \times \prod_{1=n' \neq \{i_1, \dots, i_k\}}^{M+N} F_{g_{n'}^{CNC}}(\bar{\gamma}_{th}^{CNC}) \right]. \quad (35)$$

Likewise, the asymptotic OP is as follows:

$$OP_{CNC}^{1-Asymp} = \Omega_S(N+1) + \sum_{k=1}^N \Omega_S(k) \Omega_{CNC}(N-k+1), \quad (36)$$

if $N < M$; otherwise it is equal to:

$$OP_{CNC}^{2-Asymp} = \sum_{k=1}^M \Omega_S(k) \Omega_{CNC}(N-k+1), \quad (37)$$

where

$$\Omega_S(k) = \sum_{\substack{i_1=1, \dots, i_k=1 \\ i_1 \neq \dots \neq i_k}}^M \left(\prod_{m=i_1}^{i_k} \frac{\bar{\gamma}_{th}^{CNC}}{\bar{\gamma}_{S_m D}} \right), \quad (38)$$

and

$$\Omega_{CNC}(k) = \sum_{\substack{i_1=1, \dots, i_k=1 \\ i_1 \neq \dots \neq i_k}}^N \left(\prod_{n=i_1}^{i_k} \frac{\bar{\gamma}_{th}^{CNC}}{\bar{\gamma}_n} \right). \quad (39)$$

From (36) and (37), we observe that repetition-based NCC achieves full diversity order equal to $N + 1$. Similar to the time-sharing case, this does not necessarily imply that repetition-based NCC outperforms MRS-based NCC. The respective reliability thresholds, in fact, are, in general, different, i.e., $\bar{\gamma}_{th}^{CNC} \neq \gamma_{th}$. Let, in fact, the time-slot duration of repetition-based NCC be equal to $\tau_{CNC} = T/(M + N)$. Then, the corresponding rate is equal to $\mathcal{R}_{CNC} = \mathcal{R}/(M + N)$. By re-writing it in terms of $\mathcal{R}_{MRS} = \mathcal{R}/(M + L)$, we have $\mathcal{R}_{CNC} = ((M + N)/(M + L))\mathcal{R}_{MRS} \geq \mathcal{R}_{MRS}$. As a result, $\bar{\gamma}_{th}^{CNC} = 2^{\mathcal{R}_{CNC}} - 1 \geq \gamma_{th} = 2^{\mathcal{R}_{MRS}} - 1$.

When the number of the selected relays exceeds the number of the sources, i.e., $L \geq M$, by comparing (25) and (37) we conclude that MRS-based NCC always outperforms repetition-based NCC because $\bar{\gamma}_{th}^{CNC} \geq \gamma_{th}^{MRS}$.

VII. NUMERICAL RESULTS

In this section, selected numerical results are illustrated to substantiate our findings. For ease of illustration, a symmetric network topology is considered, where $\bar{\gamma}_{S_m D} = \bar{\gamma}_{SD}, \forall m$, $\bar{\gamma}_{R_n D} = \bar{\gamma}_{RD}, \forall n$, and $\bar{\gamma}_{S_m R_n} = \bar{\gamma}_{SR}, \forall m, n$. For a given rate \mathcal{R} , the reliability thresholds are computed as discussed in Section VI.

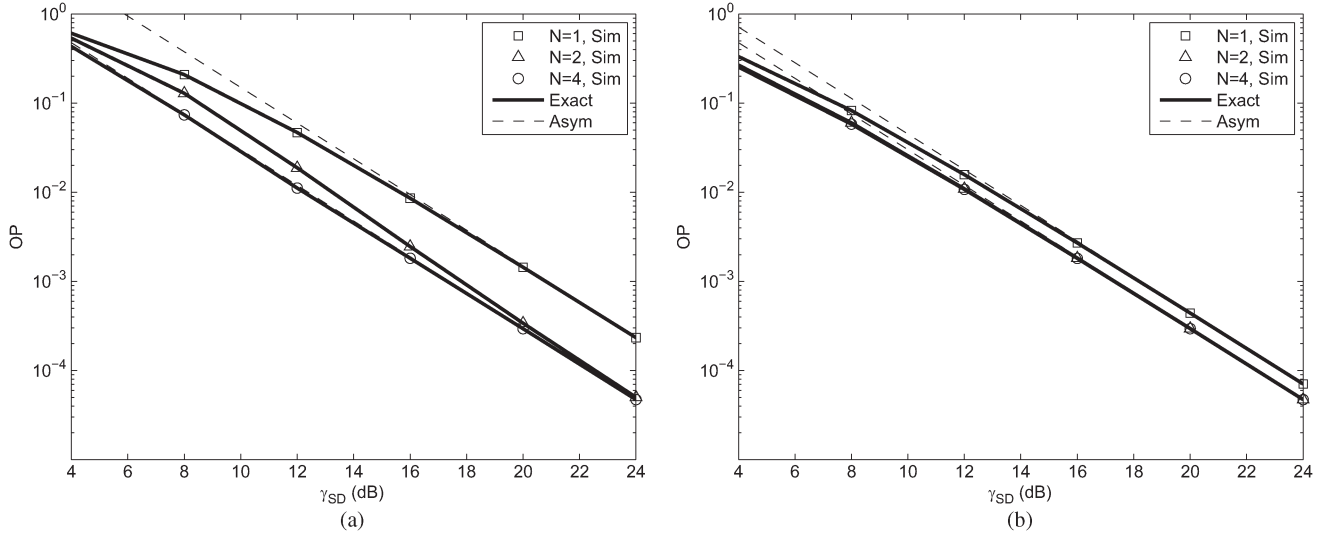


Fig. 3. OP of SRS as a function of N . Setup: $M = 3$ and $\mathcal{R} = 3/4$. (a) $\bar{\gamma}_{SD} = \bar{\gamma}_{SR} = \bar{\gamma}_{RD}$. (b) $(\bar{\gamma}_{SD}, \bar{\gamma}_{SR}, \bar{\gamma}_{RD}) = (\bar{\gamma}, \bar{\gamma} + 9 \text{ dB}, \bar{\gamma} + 9 \text{ dB})$.

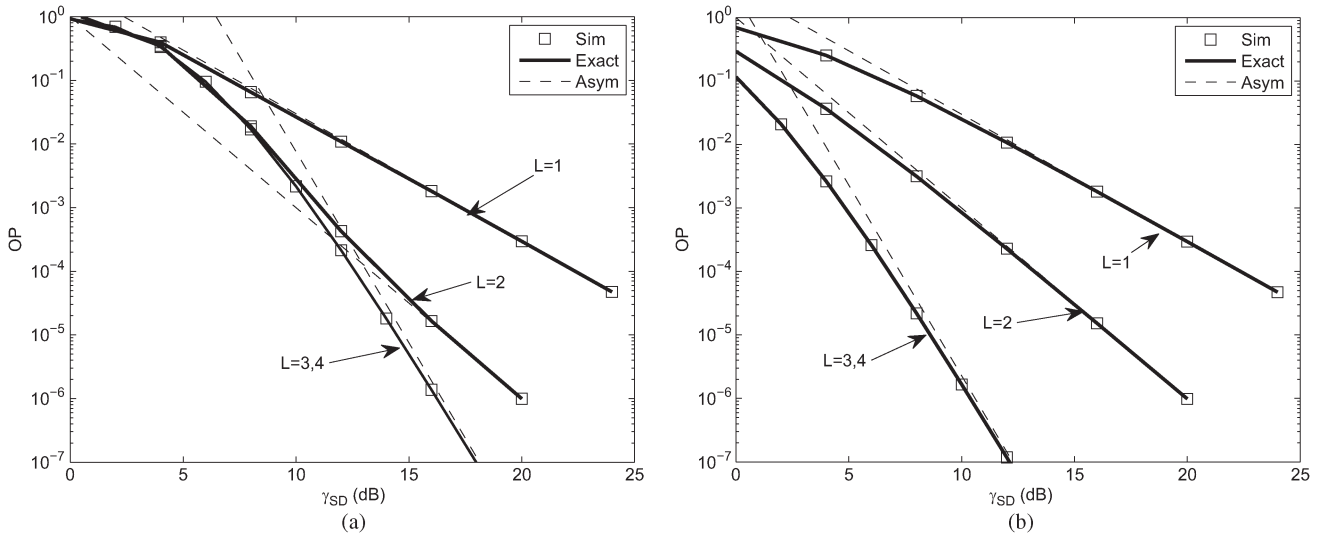


Fig. 4. OP of MRS as a function of L . Setup: $M = 3$, $N = 5$ and $\mathcal{R} = M/(M+L)$. (a) $\bar{\gamma}_{SD} = \bar{\gamma}_{SR} = \bar{\gamma}_{RD}$. (b) $(\bar{\gamma}_{SD}, \bar{\gamma}_{SR}, \bar{\gamma}_{RD}) = (\bar{\gamma}, \bar{\gamma} + 9 \text{ dB}, \bar{\gamma} + 9 \text{ dB})$.

Fig. 3 shows the OP of SRS-based NCC as a function of N . If $N = 1$, no RS is applied. It is shown that the proposed mathematical framework closely overlaps with Monte Carlo simulations and that SRS achieves second-order diversity. If the number of available relays $N > 1$ increases, SRS provides a better OP in the low-SNR but the same OP in the high-SNR. This is in agreement with Theorem 2, which states that the asymptotic OP of SRS only depends on the source-to-destination links. The gain of RS compared to the baseline setup with $N = 1$, i.e., no RS, is equal to 3 dB in Fig. 3(a) and to 1 dB in Fig. 3(b).

Fig. 4 shows the OP of MRS-based NCC as a function of L . Monte Carlo simulations confirm the accuracy of the proposed mathematical framework and the correctness of the diversity analysis. If $L < M$, in particular, MRS is not capable of achieving full diversity. The diversity order increases with L . If $L \geq M$, on the other hand, MRS achieves full diversity and almost the same OP is obtained for all values of $L \geq M$, as a result from Theorem 4.

Fig. 5 compares the OP of MRS-based NCC and repetition-based NCC as a function of L . It confirms the findings of Section VI. In particular, MRS-based NCC outperforms repetition-based NCC if $L \geq M$. If $L < M$, on the other hand, MRS-based NCC outperforms repetition-based NCC in the low-SNR regime but it provides a worse OP in the high-SNR regime because of the lower diversity order ($L+1$ instead of $N+1$).

Fig. 6 compares the OP of MRS-based NCC and time-sharing relaying. It is shown, in particular, that MRS-based NCC outperforms time-sharing relaying if the average SNR of the source-to-destination links is better than that of the relay-to-destination links.

VIII CONCLUSION

In this paper, we have studied outage probability and diversity order of a cooperative protocol that combines relay selection and network coding. A mathematical framework has

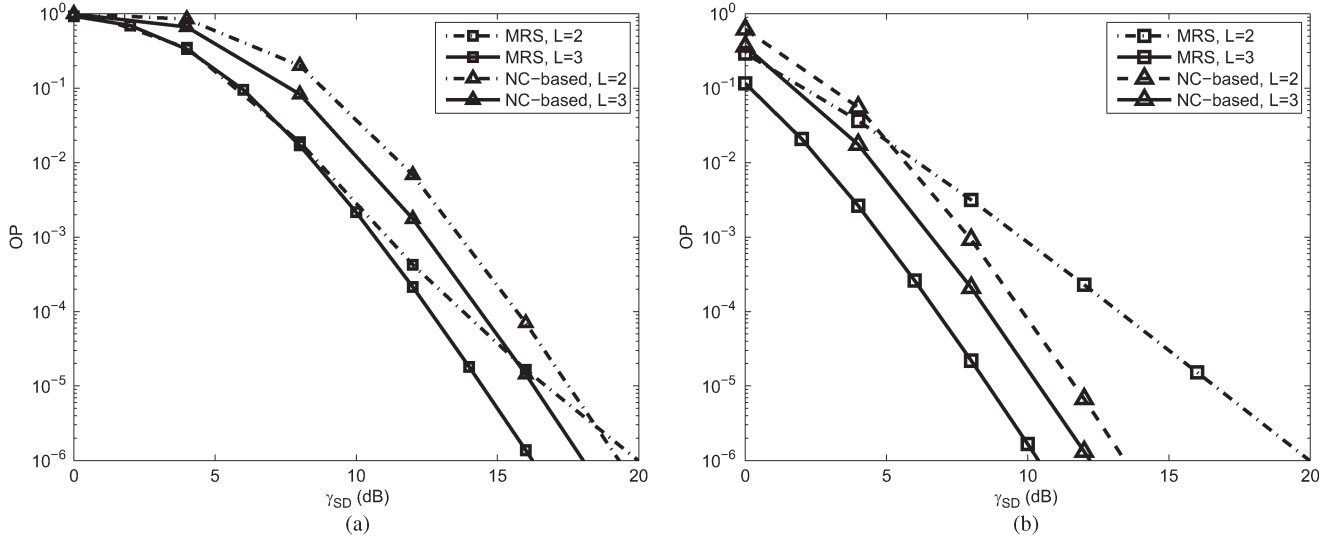


Fig. 5. OP of MRS-based NCC and repetition-based NCC: Comparison as a function of L . Setup: $M = 3$, $N = 5$, $\mathcal{R} = 3/5$ if $L = 2$ and $\mathcal{R} = 1/2$ if $L = 3$. (a) $\bar{\gamma}_{SD} = \bar{\gamma}_{SR} = \bar{\gamma}_{RD}$. (b) $(\bar{\gamma}_{SD}, \bar{\gamma}_{SR}, \bar{\gamma}_{RD}) = (\bar{\gamma}, \bar{\gamma} + 9 \text{ dB}, \bar{\gamma} + 9 \text{ dB})$.

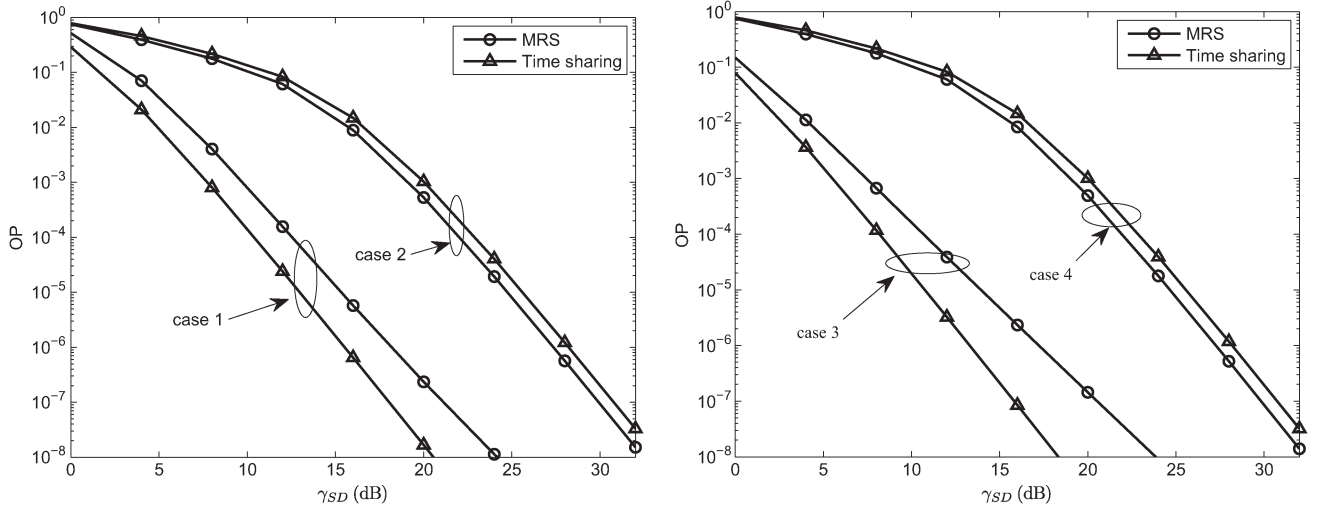


Fig. 6. OP of MRS-based NCC and time-sharing relaying. Setup: $M = 3$, $N = 3$, $L = 2$ and $\mathcal{R} = 3/5$. Case 1: $\bar{\gamma}_{SR} = \bar{\gamma}_{RD} = \bar{\gamma}_{SD}$. Case 2: $\bar{\gamma}_{SR} = \bar{\gamma}_{SD}$, $\bar{\gamma}_{RD} = \bar{\gamma}_{SD} - 20 \text{ dB}$. Case 3: $\bar{\gamma}_{SR} = \bar{\gamma}_{SD} + 20 \text{ dB}$, $\bar{\gamma}_{RD} = \bar{\gamma}_{SD}$. Case 4: $\bar{\gamma}_{SR} = \bar{\gamma}_{SD} + 20 \text{ dB}$, $\bar{\gamma}_{RD} = \bar{\gamma}_{SD} - 20 \text{ dB}$.

been provided for analyzing the system diversity order. Our analysis has shown that full diversity can be achieved if the number of active relays is at least equal to the number of sources. Otherwise, the diversity order is equal to the number of active relays plus one.

APPENDIX A
PROOF OF THEOREM 2

The proof is based on the second-order approximation of e^{-x} , $\forall x > 0$, as follows:

$$e^{-x} \approx 1 - x + \frac{x^2}{2} + \mathcal{O}[x^3]. \quad (40)$$

Let $a_m = \frac{\gamma_{th}}{\gamma_{S_m D}} > 0$, $A = \sum_{m=1}^M a_m$, and $A_{\sim m} = \sum_{m' \neq m}^M a_{m'}$.

Then, we have:

$$\prod_{m=1}^M (1 - F_{\gamma_{S_m D}}(\gamma_{th})) = \prod_{m=1}^M e^{-a_m} = e^{-A} \approx 1 - A + \frac{A^2}{2}, \quad (41)$$

and

$$\begin{aligned} & \sum_{m=1}^M F_{\gamma_{S_m D}}(\gamma_{th}) \prod_{m'=1, m' \neq m}^M (1 - F_{\gamma_{S_j D}}(\gamma_{th})) \\ & \approx \sum_{m=1}^M \left(a_m - \frac{a_m^2}{2} \right) \left(1 - A_{\sim m} + \frac{A_{\sim m}^2}{2} \right) \\ & = \sum_{m=1}^M a_m - \frac{1}{2} \sum_{m=1}^M a_m^2 - \sum_{m=1}^M a_m A_{\sim m} \\ & = A - \frac{A^2}{2} - \sum_{\substack{m=1, m'=1 \\ m \neq m'}}^M a_m a_{m'}. \end{aligned} \quad (42)$$

Let $b_n = \frac{\gamma_{th}}{\gamma_n}$ with $1 \leq n \leq N$ and $B = \prod_{n=1}^N b_n$. Then:

$$F_{g_{SR S}}(\gamma_{th}) \approx \prod_{n=1}^N \left(b_n - \frac{b_n^2}{2} \right) \approx B. \quad (43)$$

$$\left[\begin{array}{cccc} \Psi(0)F_{g_1}(\gamma_{th}) & & & \\ \Psi(1)F_{g_1}(\gamma_{th}) & \Psi(0)F_{g_2}(\gamma_{th}) & & \\ \dots & & & \\ \Psi(L-1)F_{g_1}(\gamma_{th}) & \dots & \Psi(0)F_{g_L}(\gamma_{th}) & \\ \Psi(L)F_{g_1}(\gamma_{th}) & \dots & \Psi(1)F_{g_L}(\gamma_{th}) & \Psi(0)(1-F_{g_L}(\gamma_{th})) \\ \dots & & & \\ \Psi(M-1)F_{g_1}(\gamma_{th}) & \dots & \Psi(M-L)F_{g_L}(\gamma_{th}) & \Psi(M-L-1)(1-F_{g_L}(\gamma_{th})) \end{array} \right] \quad (44)$$

$$\left[\begin{array}{cccc} \Psi(0)F_{g_1}(\gamma_{th}) & & & \\ \Psi(1)F_{g_1}(\gamma_{th}) & \Psi(0)F_{g_2}(\gamma_{th}) & & \\ \dots & & & \\ \Psi(M-1)F_{g_1}(\gamma_{th}) & \dots & \dots & \Psi(0)F_{g_M}(\gamma_{th}) \end{array} \right] \quad (45)$$

The proof follows by inserting (41), (42), and (43) in (17) and by keeping the dominant elements.

APPENDIX B PROOF OF THEOREM 3

Let divide the packets received at the destination in two groups. The first group consists of the M packets received from the sources. The second group consists of the L packets received from the selected relays. The probability that the destination is capable of decoding P packets is equal to the probability that the SNRs of P links are above the reliability threshold γ_{th} . Since these links are uniformly distributed in the two groups, this probability is given by the summation of \mathcal{C}_2^P terms.

Let $\Psi(k)$ be the probability that there are k source-to-destination links whose SNR is above the reliability threshold γ_{th} , while the SNRs of the other $M-k$ links are below γ_{th} . Since these SNRs are all independent, we obtain (23). The probability that the SNRs of $l < L$ links in \mathbf{g}_{MRS} are above the threshold is given in Lemma 2, which is equal to $F_{g_{l+1}}(\gamma_{th})$. The probability that the SNRs of all L channels in \mathbf{g}_{MRS} are above the threshold is equal to $1 - F_{g_L}(\gamma_{th})$.

Let consider the probabilities in (20). If $M > L$, the matrix of size $(M+1) \times (L+1)$ shown in (44), shown at the top of the page, can be obtained. If $L \geq M$, the matrix in (45), shown at the top of the page, can be obtained, instead. We note that the entries in the diagonals have the same $\Psi(k)$. By summing the first L diagonals in (44), we obtain the first factor in (21). By summing the other diagonals in (44), we obtain the second factor in (21). If $L \geq M$, summing the diagonals in (45) and grouping the elements with the same common part yields (22). This concludes the proof.

REFERENCES

- [1] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity—Part I: System description," *IEEE Trans. Commun.*, vol. 51, no. 11, pp. 1927–1938, Nov. 2003.
- [2] A. Bletsas, A. Khisti, D. P. Reed, and A. Lippman, "A simple cooperative diversity method based on network path selection," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 3, pp. 659–672, Mar. 2006.
- [3] M. Di Renzo, M. Iezzi, and F. Graziosi, "On diversity order and coding gain of multisource multirelay cooperative wireless networks with binary network coding," *IEEE Trans. Veh. Technol.*, vol. 62, no. 3, pp. 1138–1157, Mar. 2013.
- [4] R. Ahlswede, C. Ning, S. Y. R. Li, and R. W. Yeung, "Network information flow," *IEEE Trans. Inf. Theory*, vol. 46, no. 4, pp. 1204–1216, Apr. 2000.
- [5] Z. Ding and K. Leung, "On the combination of cooperative diversity and network coding for wireless uplink transmissions," *IEEE Trans. Veh. Technol.*, vol. 60, no. 4, pp. 1590–1601, Apr. 2011.
- [6] Y. Li, R. H. Y. Louie, and B. Vucetic, "Relay selection with network coding in two-way relay channels," *IEEE Trans. Veh. Technol.*, vol. 59, no. 9, pp. 4489–4499, Sep. 2010.
- [7] Y. Jing and H. Jafarkhani, "Single and multiple relay selection schemes and their achievable diversity orders," *IEEE Trans. Wireless Commun.*, vol. 8, no. 3, pp. 1414–1423, Mar. 2009.
- [8] S. Atapattu, Y. Jing, H. Jiang, and C. Tellambura, "Relay selection schemes and performance analysis approximations for two-way networks," *IEEE Trans. Commun.*, vol. 61, no. 3, pp. 987–998, Mar. 2013.
- [9] M. Di Renzo, M. Iezzi, and F. Graziosi, "Error performance and diversity analysis of multi-source multi-relay wireless networks with binary network coding and cooperative MRC," *IEEE Trans. Wireless Commun.*, vol. 12, no. 6, pp. 2883–2903, Jun. 2013.
- [10] M. Di Renzo, "On the achievable diversity of repetition-based and relay selection network-coded cooperation," *IEEE Trans. Commun.*, vol. 62, no. 7, pp. 2296–2313, Jul. 2014.
- [11] C. Peng, Q. Zhang, M. Zhao, Y. Yao, and W. Jia, "On the performance analysis of network-coded cooperation in wireless networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 8, pp. 3090–3097, Aug. 2008.
- [12] H. Topakkaya and W. Zhengdao, "Wireless network code design and performance analysis using diversity-multiplexing tradeoff," *IEEE Trans. Commun.*, vol. 59, no. 2, pp. 488–496, Feb. 2011.
- [13] Z. Ding, T. Ratnarajah, and K. Leung, "On the study of network coded AF transmission protocol for wireless multiple access channels," *IEEE Trans. Wireless Commun.*, vol. 7, no. 11, pp. 4568–4574, Nov. 2008.
- [14] W. Geng and T. Lv, "An opportunistic network coding cooperative scheme for wireless uplink multi-relay cooperative networks," in *Proc. Int. Symp. Wireless Pers. Multimedia Commun.*, Sep. 2012, pp. 148–152.
- [15] W. Guan and K. Liu, "Diversity analysis of analog network coding with multi-user interferences," *IEEE Trans. Wireless Commun.*, vol. 12, no. 2, pp. 668–679, Feb. 2013.
- [16] M. K. Simon and M.-S. Alouini, *Digital communication over fading channels*, 2nd ed. London, U.K.: Wiley, 2005.
- [17] R. C. Singleton, "Maximum distance Q-Nary codes," *IEEE Trans. Inf. Theory*, vol. 10, no. 2, pp. 116–118, Feb. 1964.
- [18] A. Behnad, A. Rabiei, N. Beaulieu, and H. Hajizadeh, "Generalized analysis of dual-hop DF opportunistic relaying with randomly distributed relays," *IEEE Commun. Lett.*, vol. 17, no. 6, pp. 1057–1060, Jun. 2013.



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