On Relay Assignment in Network-Coded Cooperative Systems

Xuehua Zhang, Ali Ghrayeb and Mazen Hasna

***Abstract*—We consider in this paper relay assignment for cooperative systems with multiple two-way relay channels. The nodes corresponding to one two-way relay channel (henceforth referred to as *pair*) communicate with each other through a relay. The relays use *network coding* to simultaneously transmit the signals corresponding to the pairs they are assigned to. We propose two relay assignment schemes. One scheme considers all possible relay assignment permutations and selects the one that yields the best performance, and the other one considers only a subset of these permutations and selects the best one. The advantage of the latter is that it results in a significant reduction in computational complexity, in addition to making the analysis more tractable. We analyze the performance of these schemes over asymmetric independent Rayleigh fading channels. We also consider semi-symmetric and symmetric channels as special cases. We derive closed-form expressions for the end-to-end bit error rate performance for all scenarios and show that the full diversity order is achieved, which is the number of available relays. We present several examples to verify the theoretical results.**

***Index Terms*—Cooperative networks, network coding, relay assignment, two-way relay channels.**

I. Introduction

THE concept of network coding was first proposed by Ahlswede, *et. al*idea is that the intermediate node linearly combines the received data instead of sending them directly. Various relaying protocols have been proposed for the two-way relaying channels, whereby two nodes exchange information between each other through one or more relays. The relay nodes normally operate either in the decode-and-forward (DF) or amplify-and-forward (AF) mode. All proposed protocols that use network coding can be classified into two types: Three-step schemes [2], [3], and two-step schemes [4]. In the former schemes, the relay receives and decodes the bits received from both nodes in the first two steps. In the third step, the relay applies exclusive-or (XOR) to both bits and broadcasts the resulting bit to both nodes. This results in saving one step in this way as compared to traditional relaying (without network coding). The authors in [5] and [6] study how to cope with the performance degradation due to the asymmetry in the channel, i.e., when the relay is not equally far away from the nodes. In [5], a solution to the time optimization of each phase is given, whereas in [6], hierarchical modulation at one source is employed. In the two-step schemes, the relay only decodes the sum of the signals received and maps it to a corresponding zero or one. In [7], a two-step AF scheme named analog network coding is presented.

Another related direction of research in cooperative communications is *selection diversity*, which is a fundamental diversity technique that can be found in many works in the literature. A relay selection scheme termed opportunistic relaying based on the end-to-end channel instantaneous quality is proposed in [8]. For this relay selection scheme, there are two main relay selection methods: Proactive opportunistic relaying and reactive opportunistic relaying [9]. The main differences between these two methods are as follows. For proactive opportunistic relaying, the relaying selection is performed before transmission. But for reactive opportunistic relaying, the relay selection is performed after transmission and this relay must be one of the relays that successfully decoded the signal received from the source. The performance of these two schemes with or without direct path and AF relaying or DF relaying are studied in [9]-[15], and it is shown that the full diversity order is achieved. In [14], the authors extend reactive opportunistic relaying to a network environment, which involves multiple simultaneous unidirectional transmitting source-destination pairs. Relay assignment for multiple pairs in relay networks is also considered in [16] and [17].

Recently, some efforts have been made to exploit selection diversity with network coding in cooperative networks [18], [19]. Relay selection for bidirectional DF relaying is first studied in [18]. In [19], the authors study the performance of two-way AF relaying with relay selection similar to the opportunistic relaying scheme proposed in [8]. Besides these papers, there are some other papers that study the performance of network coding with relay selection for multiple source-destination pairs. In [20] and [21], the performance of the XOR-based network coding combined with relay selection for multiple source-destination pairs is analyzed. Only the best relay is chosen to help all pairs. The best relay is selected based on the end-to-end instantaneous channel gains, which is similar to the proactive opportunistic relaying proposed in [9].

The authors in [22] propose another network coding scheme for relay selection with multiple source-destination pairs. Unlike [20] and [21], the scheme in [22] is based on selecting the best relay from the relays that have successfully decoded the message from all sources, which is similar to the reactive opportunistic relaying scheme proposed in [9]. However, the

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schemes in [20] and [21] are somewhat impractical since the destination is assumed to be able to have correctly received the messages sent by all the other sources. The scheme in [22] does not have this assumption where it transmits a random linear combination of the columns using an underlying space time block codes (STBC) matrix as a network coding scheme at the relay [23]. But as the number of pairs increases, the detection complexity of this scheme becomes unacceptable. Also, we notice that the best relay is chosen from the relays that have successfully decoded the message from all the sources, which leads to a nonzero probability that there will be no qualified relays to select from. So although both two schemes are attractive due to their high throughput, they lack practicality.

In light of the above, it is clear that two-way relaying with or without relay selection has been largely studied in many aspects.[1] However, to the best of our knowledge, no work has been done to solve the following problem: *How to assign relays, in a network setting, to the network pairs in conjunction with network coding*. This is addressed in this paper.[2] In particular, we propose two relay assignment schemes. One is based on the entire set of relay assignment permutations, and another based on a subset of these permutations. Comparing with the work of [14], there are two main differences. Firstly, the problem that we are trying to solve here is the relay assignment problem for two-way relaying with network coding, while the relay assignment problem in [14] is for one-way relaying without network coding. The schemes in [14] can not be applied directly to solve the problem at hand. Secondly, although both of our relay assignment schemes are based on the end-to-end channel qualities, they are based on proactive opportunistic relaying, while the schemes in [14] are based on reactive opportunistic relaying. Since the relay assignment in our schemes is done before the actual transmission, only the selected relays need to decode the information of the pairs that they are helping, while for the schemes in [14], all the relays have to try to decode all the information from all sources and tell the destinations whether they have successfully decoded or not, which introduces a computational burden at the relays.[3]

We examine the performance of the proposed assignment schemes on symmetric and asymmetric independent Rayleigh fading channels. In the symmetric case, all subchannels have the same average signal-to-noise ratio (SNR), whereas in the asymmetric case, the subchannels have different SNRs. We analyze the performance of these assignment schemes and derive a closed form expression for the end-to-end bit error rate performance. We show that the maximum diversity order is achieved, which is the number of relays. We also present several examples through which we validate the theoretical results.

The remainder of the paper is organized as follows. The system model is presented in Section II. In Section III, the proposed relay assignment schemes are presented. We analyze the performance of these schemes assuming binary phase shift keying (BPSK) in Section IV. The diversity order of the system, based on the suboptimal criterion, is derived in Section V. We present several numerical examples in Section VI. Section VII concludes the paper.

[1]As two-way relaying is a basic building block in most wireless networks, multiple two-way relay channels coexist in practical systems such as wireless sensor network and vehicular ad-hoc networks (VANETs), to name a few.

[2]We remark that relay assignment for multiple-pair networks was considered in [26], but without network coding.

[3]Some work had been done to remedy the impact of error propagation due to imperfect detection at the relay nodes (see [24], [25] and references therein.)

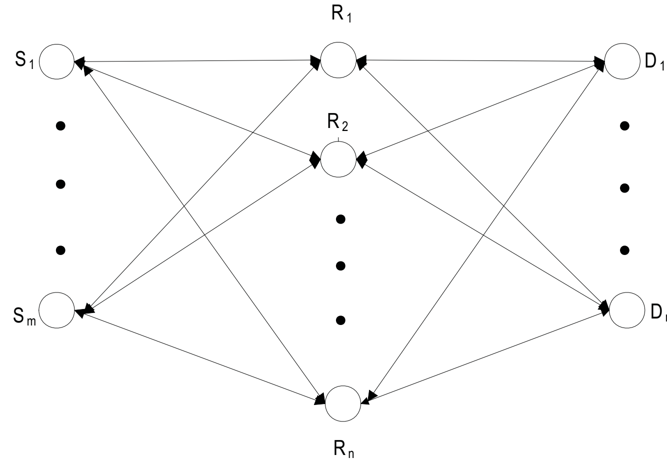

Fig. 1. A cooperative network with m bidirectional communication pairs and n relays.

II. System Model

The system model considered in this paper is shown in Fig. 1. As shown in the figure, the network consists of m pairs (i.e., m two-way relay channels) and n relay nodes where $n \geq m$. Again, the latter assumption is justified because any node in a network can serve as a relay node. The nodes of each pair communicate with each other through one relay node using orthogonal subchannels. For simplicity, we assume that there is no direct path between the source and destination nodes. However, the relay assignments schemes analyzed here can be extended to the case when there is a direct path.

Each of the nodes is equipped with a single antenna and operates in a half-duplex mode. We assume that all nodes use BPSK signaling. In the first time slot, one of the nodes of each pair transmits its signal. That is, m nodes transmit simultaneously in the first time slot using frequency division multiple access (FDMA) [27]. In the second time slot, the remaining m nodes transmit simultaneously their signals to the relays. We assume that a central controller in the network has the channel state information (CSI) of all the links. We acknowledge that the complexity of this scheme grows with the number of pairs in the network, which is a known problem for such networks. The best m relays are then assigned to the m pairs where one relay is intended to serve one pair. Each relay node decodes the two received signals (over the two time slots), XORs the decoded signals, and broadcasts the resulting signal to all nodes. Note that the selected m relays will have to transmit using orthogonal channels (either in time or frequency).

The network subchannels are assumed to experience independent slow and frequency non-selective Rayleigh fading. Let $h_{S_iR_j}$, $h_{D_iR_j}$, $h_{R_jS_i}$ and $h_{R_jD_i}$ (for $i = 1, \ldots, m,\ j = 1, \ldots, n$) denote the fading coefficients between the ith source$-j$th relay, ith destination$-j$th relay, jth relay$-i$th source and jth relay$-i$th destination, respectively. We consider both independent identically distributed (i.e., symmetric) and independent but non-identically distributed (i.e., asymmetric) Rayleigh fading channels over all transmitting pairs and relays.[4] To avoid ambiguity, we refer to one of the nodes of each pair as source (S) and the other node as destination (D), although it is a two-way communication between S and D.

Let $y_{S_iR_j}$ and $y_{D_iR_j}$ denote the received signals at the jth relay from the ith source and ith destination (over the two time slots), respectively. These signals can be expressed as

$$y_{S_iR_j} = \sqrt{\rho_{i,j}} h_{S_iR_j} x_{S_i} + n_{S_iR_j},$$

and

$$y_{D_iR_j} = \sqrt{\rho_{i,j}} h_{D_iR_j} x_{D_i} + n_{D_iR_j},$$

respectively, where $\rho_{i,j}$ denotes the average SNR of the (i,j)th subchannel, x_{S_i} denotes the transmitted signal from node S_i, x_{D_i} denotes the transmitted signal from node D_i, and $n_{S_iR_j}$ and $n_{D_iR_j}$ are additive white complex Gaussian noise (AWGN) samples with zero mean and unit variance. The relay then uses maximum likelihood (ML) detection to detect the two signals (arriving from the pair nodes over two time slots). That is, $\hat{x}_{S_iR_j}$ =sign($\Re e\{y_{S_iR_j} h^*_{S_iR_j}\}$), and $\hat{x}_{D_iR_j}$ =sign($\Re e\{y_{D_iR_j} h^*_{D_iR_j}\}$).

After the two signals are detected at the relay nodes, they are XORed as $x_{R_j} = \hat{x}_{S_iR_j} \oplus \hat{x}_{D_iR_j} = -(\hat{x}_{S_iR_j}\hat{x}_{D_iR_j})$, and the resulting signal is broadcasted to all nodes in the third time slot. The signals received at the source and destination nodes of each pair are expressed as

$$y_{R_jS_i} = \sqrt{\rho_{j,i}} h_{R_jS_i} x_{R_j} + n_{R_jS_i},$$

and

$$y_{R_jD_i} = \sqrt{\rho_{j,i}} h_{R_jD_i} x_{R_j} + n_{R_jD_i},$$

respectively. Consequently, the final decoded bits at the source and destination of each pair are expressed as $\hat{x}_{S_i}$ =sign($\Re e\{-x_{S_i} y_{R_jS_i} h^*_{R_jS_i}\}$), and $\hat{x}_{D_i}$ =sign($\Re e\{-x_{D_i} y_{R_jD_i} h^*_{R_jD_i}\}$), respectively.

III. Relay Assignment Criteria

In this section, we discuss two relay assignment criteria. The first criterion considers all possible relay permutations, whereas the second criterion limits the search over a subset of the available permutations. Details of these criteria are in order.

A. Full Set (optimal) Selection

The optimal assignment scheme depends on the subchannel instantaneous SNR between the relay nodes and the pair nodes, namely, $\gamma_{S_iR_j}$, $\gamma_{R_jD_i}$, $\gamma_{D_iR_j}$, and $\gamma_{R_jS_i}$ (for $i = 1, \ldots, m$, $j = 1, \ldots, n$) where $\gamma_{S_iR_j} = \rho_{i,j} \left| h_{S_iR_j} \right|^2$. To simplify the notation, let $\boldsymbol{\gamma}_j^i$ denote the set $\{\gamma_{S_iR_j}, \gamma_{R_jD_i}, \gamma_{D_iR_j}, \gamma_{R_jS_i}\}$, which is the set of the instantaneous SNRs between the jth relay and the nodes of the ith pair. The objective here is to optimize the end-to-end bit error rate performance. Since there are two hops separating the end nodes in each pair, the weaker link is the one that dominates the end-to-end bit error rate performance. This certainly applies to all pairs. Therefore, the optimal relay assignment scheme is the one that results in the best subchannel among the weakest ones.

To elaborate, let Φ be the set containing all assignment permutations. Given that there are m pairs and n relays, the size of Φ is obviously $P_m^n = \frac{n!}{(n-m)!}$. Each element of Φ consists of all the fading coefficients ($4m$ of them since there are m pairs and each pair has four subchannels) corresponding to that particular relay assignment. To simplify the presentation, let ϕ_k denote the kth element of Φ for $k = 1, 2, \ldots, P_m^n$, and let $\gamma_{k,\min}$ denote the smallest element in ϕ_k, i.e., the weakest subchannel. Accordingly, the optimal assignment, denoted by ϕ_{k^*}, has index k^*

$$k^* = \arg\max_k \left\{\gamma_{k,\min},\ k = 1, 2, \ldots, P_m^n\right\}. \qquad (1)$$

To elaborate, consider the example in which $m = 3$ and $n = 4$. Consequently, there are 24 possible relay assignment permutations, which are illustrated in Table I. In the table, the first entry of each row indicates the relay assigned to the first pair, the second is the relay assigned to the second pair and the third is the relay assigned to the third pair. To relate Φ to Table I, consider the first row of the table. The three entries of this row correspond to $\boldsymbol{\gamma}_1^1$, $\boldsymbol{\gamma}_2^2$ and $\boldsymbol{\gamma}_3^3$, respectively. Each of these elements represents four fading coefficients, as defined before, thus there are 12 fading coefficients comprising ϕ_1. Obviously, $\gamma_{1,\min}$ in (1) is the minimum of those 12 coefficients. Once the minimum of each row is obtained, the permutation corresponding to the largest is selected.

While this assignment scheme is optimal, it suffers from high complexity because it is essentially brute-force. For example, when $n = m = 10$, there are $P_m^n = 3628800$ permutations to search over. In addition, there is correlation between certain rows of Φ, which makes the performance analysis difficult. For instance, rows one and five are correlated since in both cases, R_1 is assigned to the first pair. Such correlation makes it extremely difficult to find a closed form expression for the probability density function (pdf) of the resulting fading coefficients. These reasons motivate us to consider a subset assignment scheme, described next, whereby the permutations considered are not correlated.

B. Subset (suboptimal) Selection

The objective here is to divide the set Φ into subsets such that the correlation among the permutations within a subset is eliminated. Then the best permutation within one subset is selected. The number of subsets is $N = P_m^n/n$, which results in a significant reduction in complexity. For instance, when $n = m = 10$, the number of permutations to consider reduces from 3628800 to 10. Another advantage of this selection criterion is the fact it becomes easier to obtain the pdf of the coefficients corresponding to the selected permutation since such permutations are mutually independent. The disadvantage is some degradation in performance, as we will demonstrate later.

[4]The assumption of having four independent subchannels for each pair can be justified since FDMA is used for the uplink and downlink channels.

TABLE I
ALL POSSIBLE RELAY ASSIGNMENT PERMUTATIONS FOR $m = 3$ AND $n = 4$.

	pair 1	pair 2	pair 3
subset 1	R_1	R_2	R_3
	R_2	R_3	R_4
	R_3	R_4	R_1
	R_4	R_1	R_2
subset 2	R_1	R_3	R_2
	R_2	R_4	R_3
	R_3	R_1	R_4
	R_4	R_2	R_1
subset 3	R_1	R_2	R_4
	R_2	R_3	R_1
	R_3	R_4	R_2
	R_4	R_1	R_3
subset 4	R_1	R_4	R_2
	R_2	R_1	R_3
	R_3	R_2	R_4
	R_4	R_3	R_1
subset 5	R_1	R_3	R_4
	R_2	R_4	R_1
	R_3	R_1	R_2
	R_4	R_2	R_3
subset 6	R_1	R_4	R_3
	R_2	R_1	R_4
	R_3	R_2	R_1
	R_4	R_3	R_2

Remark 1: The full set and subset assignment criteria are equivalent for the following cases: $m = 1$, any n; and $m = n = 2$. However, for most other cases, especially as n increases, there will be a performance degradation since the number of permutations to be searched over will be less.

In the following, we shall outline the steps that lead to dividing Φ into the desired subsets. In the process, we will refer to Table I to make things clear.

1) Construct N subsets, each having n permutations, i.e., rows. There are m entries in each row.
2) Fill the first entry of the first row of each subset with one relay, and this relay should be the same in all of these entries. Note that this relay could be any of the possible relays, but once one is selected, it should be the same. For instance, In Table I, this relay is R_1.
3) Fill the remaining $m-1$ entries of the first row of each subset with all other permutations of the remaining $n-1$ relays. There are P_{m-1}^{n-1} of such permutations. Referring to Table I, there are six permutations.
4) Fill the remaining entries of each column of each subset with the remaining relays without repetition. For each subset, this can be accomplished by starting with the first entry of each column and increase the index of the relay as you go down until all relays are used up. This process ensures that a relay is used only once in any given column and any given row, which is key to eliminate correlation among the permutations of a subset. This should be clear from Table I.

IV. PERFORMANCE ANALYSIS

As mentioned above, due to the correlation between some of the elements of Φ, it is not easy to obtain a closed form expression for the pdf of the coefficients corresponding to the selected permutation. However, when such correlation is not present, obtaining such pdf is straightforward. As such, although we can not analyze the optimal scheme, the analysis of the subset scheme gives a performance upper bound on that of the optimal one. In this section, we analyze the end-to-end bit error rate performance with the subset assignment scheme over asymmetric Rayleigh fading channels. We also extend this analysis to the semi-symmetric and symmetric cases. We first derive a closed form expression for the bit error rate, and then derive an upper bound on the bit error rate to demonstrate that the full diversity order is achieved (the latter is done in Section V). Throughout this section, we assume that all nodes use BPSK.

A. The End-to-End Bit Error Rate Performance

There are two ways of having an error at the relay. When the signal from the source to the relay is detected correctly, but the signal from the destination to the relay is detected incorrectly. The second scenario is the opposite of the first. However, when both signals are in error or both are correct, the relay is not in error. Consequently, the bit error probability at the selected relay R can be obtained as

$$P_{e,R} = P_{e,S_iR}\left(1 - P_{e,D_iR}\right) + P_{e,D_iR}\left(1 - P_{e,S_iR}\right), \quad (2)$$

where P_{e,S_iR} is the probability of making an error over the $S_i - R$ link. The rest of the variables are similarly defined.

There are also two ways of making an error at either node of each pair. When the relayed bit is in error and this erroneous bit is received correctly by either node of each pair, and when the relayed bit is correct but is flipped during transmission. In this case, the bit error rate at node S_i is expressed as

$$P_{e,S_i} = \left(1 - P_{e,RS_i}\right) P_{e,R} + \left(1 - P_{e,R}\right) P_{e,RS_i}. \quad (3)$$

Plugging (2) into (3), we have

$$\begin{aligned} P_{e,S_i} = {} & P_{e,S_iR}\left(1 - P_{e,RS_i}\right)\left(1 - P_{e,D_iR}\right) \\ & + P_{e,D_iR}\left(1 - P_{e,RS_i}\right)\left(1 - P_{e,S_iR}\right) \\ & + P_{e,RS_i} - P_{e,S_iR}P_{e,RS_i}\left(1 - P_{e,D_iR}\right) \\ & - P_{e,RS_i}P_{e,D_iR}\left(1 - P_{e,S_iR}\right). \end{aligned} \quad (4)$$

Similarly, we can express the error rate expression at node D_i as

$$\begin{aligned} P_{e,D_i} = {} & P_{e,S_iR}\left(1 - P_{e,RD_i}\right)\left(1 - P_{e,D_iR}\right) \\ & + P_{e,D_iR}\left(1 - P_{e,RD_i}\right)\left(1 - P_{e,S_iR}\right) \\ & + P_{e,RD_i} - P_{e,S_iR}P_{e,RD_i}\left(1 - P_{e,D_iR}\right) \\ & - P_{e,RD_i}P_{e,D_iR}\left(1 - P_{e,S_iR}\right). \end{aligned} \quad (5)$$

In order to get the expression of P_{e,S_i} and P_{e,D_i}, we need to get expressions for P_{e,S_iR}, P_{e,D_iR}, P_{e,RS_i}, and P_{e,RD_i}.

In the following subsections, we consider the performance of various scenarios. We first start with the case when the subchannels are independent, non-identical Rayleigh fading (i.e., asymmetric). We then consider the semi-symmetric case in which the $S_i - R$ links are identical, the $D_i - R$ links are identical, the $R - S_i$ links are identical, and the $R - D_i$ links, but these four sets of subchannels are non-identical. We also consider the case when all channels are symmetric, i.e., independent and identical. Clearly, the latter two cases are special cases of the asymmetric case.

B. Asymmetric Channels

We now find expressions for P_{e,S_iR}, P_{e,D_iR}, P_{e,RS_i}, and P_{e,RD_i} so that we can get closed-form expressions for P_{e,S_i} and P_{e,D_i} defined by (4) and (5), respectively. To be able to do so, we need to find the pdf of the random variables involved, namely, γ_{S_iR}, γ_{D_iR}, γ_{RS_i} and γ_{RD_i}. Although these variables are independent and different (on average), their pdfs will be similar where we can use one expression to express the four pdfs. As such, to make the presentation simpler, we denote these variables by γ_{ik} for $k = 1, 2, 3, 4$ where $\gamma_{i1} = \gamma_{S_iR}$, $\gamma_{i2} = \gamma_{D_iR}$, $\gamma_{i3} = \gamma_{RS_i}$, and $\gamma_{i4} = \gamma_{RD_i}$.

The pdf of γ_{ik} can then be expressed as [21]

$$\begin{aligned} f_{\gamma_{ik}}(\gamma) \;=\; & \sum_{j=1}^{n} \lambda_{ij,k}\left(\lambda_j - \lambda_{ij,k}\right) e^{-\lambda_{ij,k}\gamma} \\ & \cdot \int_0^{\gamma} \left[e^{-(\lambda_j - \lambda_{ij,k})\theta} \prod_{m \neq j} \left(1 - e^{-\lambda_m \theta}\right)\right] d\theta \\ & + \sum_{j=1}^{n} \left[\lambda_{ij,k} e^{-\lambda_j \gamma} \prod_{m \neq j}\left(1 - e^{-\lambda_m \gamma}\right)\right], \end{aligned} \tag{6}$$

where $\lambda_{ij,1} \triangleq \frac{1}{\overline{\gamma}_{S_iR_j}}$, $\lambda_{ij,2} \triangleq \frac{1}{\overline{\gamma}_{D_iR_j}}$, $\lambda_{ij,3} \triangleq \frac{1}{\overline{\gamma}_{R_jS_i}}$, and $\lambda_{ij,4} \triangleq \frac{1}{\overline{\gamma}_{R_jD_i}}$) (for $i = 1, \ldots, m,\ j = 1, \ldots, n$) and $\lambda_j \triangleq \sum_{i=1}^{m} (\lambda_{ij,1} + \lambda_{ij,2} + \lambda_{ij,3} + \lambda_{ij,4})$. $\overline{\gamma}_{S_iR_j} = \rho_{i,j} E\left[\left|h_{S_iR_j}\right|^2\right]$ is the average SNR for the $S_i - R_j$ link. The other terms are similarly defined.

After some manipulations and carrying out the integration, $f_{\gamma_{ik}}(\gamma)$ can be simplified as

$$\begin{aligned} f_{\gamma_{ik}}(\gamma) \;=\; & \sum_{j=1}^{n} \sum_{\tau \in T_j^n} \operatorname{sign}(\tau) \frac{\lambda_{ij,k}\left(\lambda_j - \lambda_{ij,k}\right)}{\lambda_j - \lambda_{ij,k} + \tau} \\ & \cdot e^{-\lambda_{ij,k}\gamma}\left(1 - e^{-(\lambda_j - \lambda_{ij,k} + \tau)\gamma}\right) \\ & + \sum_{j=1}^{n} \sum_{\tau \in T_j^n} \operatorname{sign}(\tau) \lambda_{ij,k} e^{-(\lambda_j + \tau)\gamma}, \end{aligned} \tag{7}$$

where the set T_j^n is obtained by expanding the product $\prod_{m \neq j}(1 - e^{-\lambda_m \gamma})$ and then taking the logarithm of each term, and $\operatorname{sign}(\tau)$ corresponds to the sign of each term in the expansion [28]. That is,

$$T_j^n = \left\{ \tau : \prod_{\substack{m=1 \\ m \neq j}}^{n} (1 - e^{-\lambda_m \gamma}) = \sum_{\tau \in T_j^n} \operatorname{sign}(\tau) e^{-\tau\gamma} \right\}. \tag{8}$$

The moment generating function (MGF) of γ_{ik} can be calculated as [29]

$$M_{\gamma_{ik}}(s) = \int_0^{\infty} e^{-s\gamma} f_{\gamma_{ik}}(\gamma)\, d\gamma. \tag{9}$$

Plugging (7) into (9) and carrying out the integration, we have

$$\begin{aligned} M_{\gamma_{ik}}(s) \;=\; & \sum_{j=1}^{n} \sum_{\tau \in T_j^n} \operatorname{sign}(\tau) \frac{\lambda_{ij,k}\left(\lambda_j - \lambda_{ij,k}\right)}{\lambda_j - \lambda_{ij,k} + \tau} \\ & \cdot \left(\frac{1}{\lambda_{ij,k} + s} - \frac{1}{\lambda_j + \tau + s} \right) \\ & + \sum_{j=1}^{n} \sum_{\tau \in T_j^n} \operatorname{sign}(\tau) \frac{\lambda_{ij,k}}{\lambda_j + \tau + s}. \end{aligned} \tag{10}$$

The average bit error probability (for BPSK) is then given by [29]

$$P_{e,k} = \frac{1}{\pi} \int_0^{\pi/2} M_{\gamma_{ik}}\left(\frac{1}{\sin^2\theta}\right) d\theta. \tag{11}$$

Plugging (10) into (11) and after some manipulations, $P_{e,ik}$ can be expressed as

$$\begin{aligned} P_{e,ik} \;=\; & \sum_{j=1}^{n} \sum_{\tau \in T_j^n} \operatorname{sign}(\tau) \frac{\lambda_{ij,k}(\lambda_j - \lambda_{ij,k})}{\lambda_j - \lambda_{ij,k} + \tau} \\ & \cdot \left(\frac{1}{\lambda_{ij,k}} I_1\left(\frac{1}{\lambda_{ij,k}}\right) - \frac{1}{\lambda_j + \tau} I_1\left(\frac{1}{\lambda_j + \tau}\right)\right) \\ & + \sum_{j=1}^{n} \sum_{\tau \in T_j^n} \frac{\operatorname{sign}(\tau)\lambda_{ij,k}}{\lambda_j + \tau} I_1\left(\frac{1}{\lambda_j + \tau}\right), \end{aligned} \tag{12}$$

where $I_1(c)$ is given as [29]

$$I_1(c) = \frac{1}{\pi} \int_0^{\pi/2} \frac{\sin^2\theta}{\sin^2\theta + c} d\theta = \frac{1}{2}\left(1 - \sqrt{\frac{c}{1+c}}\right). \tag{13}$$

Note that when $k = 1, 2, 3, 4$, $P_{e,ik}$ corresponds to P_{e,S_iR}, P_{e,D_iR}, P_{e,RS_i}, and P_{e,RD_i} respectively. Plugging these expressions in (4), we obtain the end-to-end bit error rate expression at node S_i. Similarly, we can get the bit error rate expression at node D_i using (5).

C. Semi-symmetric Channels

In this case, it is assumed that all subchannels between the relay nodes and S_i for $i = 1, 2, \ldots, m$ have the same average SNR; and all subchannels between the relay nodes and D_i for $i = 1, 2, \ldots, m$ have the same average SNR. As such, the bit error rate performance at all S_i for $i = 1, 2, \ldots, m$ is the same. The same is true for all D_i for $i = 1, 2, \ldots, m$. However, the performance at the nodes of the same pair can be different.

We now define $\lambda_1 \triangleq \frac{1}{\overline{\gamma}_{SR}}$, $\lambda_2 \triangleq \frac{1}{\overline{\gamma}_{DR}}$, $\lambda_3 \triangleq \frac{1}{\overline{\gamma}_{RS}}$ and $\lambda_4 \triangleq \frac{1}{\overline{\gamma}_{RD}}$. Also, let γ_k for $k = 1, 2, 3, 4$ represent γ_{SR}, γ_{DR}, γ_{RS} and γ_{RD}, respectively. Note that we dropped the indices from these variables because the performance is the same for all pairs (as explained before). Accordingly, (6) can be rewritten as

$$\begin{aligned} f_{\gamma_k}(\gamma) \;=\; & n\lambda_k\left(m\lambda - \lambda_k\right) e^{-\lambda_k \gamma} \\ & \cdot \int_0^{\gamma} \left[e^{-(m\lambda - \lambda_k)\theta} (1 - e^{-m\lambda\theta})^{n-1}\right] d\theta \\ & + n\lambda_k e^{-m\lambda\gamma}\left(1 - e^{-m\lambda\gamma}\right)^{n-1}, \end{aligned} \tag{14}$$

where $\lambda = \lambda_1 + \lambda_2 + \lambda_3 + \lambda_4$. Applying binomial expansion to $f_{\gamma_k}(\gamma)$ and after some simple algebraic manipulations, (14) can be expressed as

$$\begin{aligned} f_{\gamma_k}(\gamma) &= \sum_{j=0}^{n-1} (-1)^j \binom{n-1}{j} \frac{n\lambda_k e^{-\lambda_k \gamma}(m\lambda - \lambda_k)}{m\lambda - \lambda_k + m\lambda j} \\ &\quad \cdot (1 - e^{-(m\lambda - \lambda_k + m\lambda j)\gamma}) \\ &\quad + n\lambda_k \sum_{j=0}^{n-1} (-1)^j \binom{n-1}{j} e^{-m\lambda(j+1)\gamma}. \end{aligned} \tag{15}$$

Plugging (15) into (9) and carrying out the integration, we have

$$\begin{aligned} M_{\gamma_k}(s) &= \sum_{j=0}^{n-1} (-1)^j \binom{n-1}{j} \frac{n\lambda_k (m\lambda - \lambda_k)}{m\lambda - \lambda_k + m\lambda j} \\ &\quad \cdot \left(\frac{1}{\lambda_k + s} - \frac{1}{m\lambda(j+1) + s} \right) \\ &\quad + \sum_{j=0}^{n-1} (-1)^j \binom{n-1}{j} \frac{n\lambda_k}{m\lambda(j+1) + s}. \end{aligned} \tag{16}$$

Plugging (16) into (11) and after some manipulations, the bit error rate can be expressed as

$$\begin{aligned} P_{e,k} &= \sum_{j=0}^{n-1} (-1)^j \binom{n-1}{j} \frac{n\lambda_k (m\lambda - \lambda_k)}{m\lambda - \lambda_k + m\lambda j} \\ &\quad \cdot \left(\frac{1}{\lambda_k} I_1\left(\frac{1}{\lambda_k}\right) - \frac{1}{m\lambda(j+1)} I_1\left(\frac{1}{m\lambda(j+1)}\right) \right) \\ &\quad + \sum_{j=0}^{n-1} (-1)^j \binom{n-1}{j} \frac{n\lambda_k}{m\lambda(j+1)} I_1\left(\frac{1}{m\lambda(j+1)}\right), \end{aligned} \tag{17}$$

where $P_{e,k}$ for $k = 1, 2, 3, 4$ correspond to $P_{e,SR}$, $P_{e,DR}$, $P_{e,RS}$, and $P_{e,RD}$, respectively. Then plugging the resulting expressions into (4) and (5), we have the end to end bit error probability at node S and node D, respectively.

D. Symmetric Channels

For independent, identical Rayleigh fading channels, the average SNRs for all channel is the same, i.e., λ_k defined just after (6) are the same, and define $\beta \triangleq \lambda_k$, implying that $\lambda = 4\beta$. Consequently, (17) simplifies to

$$\begin{aligned} P_e &= \sum_{j=0}^{n-1} (-1)^j \binom{n-1}{j} \frac{n\beta(4m-1)}{4m - 1 + 4mj} \\ &\quad \cdot \left(\frac{1}{\beta} I_1\left(\frac{1}{\beta}\right) - \frac{1}{4m\beta(j+1)} I_1\left(\frac{1}{4m\beta(j+1)}\right) \right) \\ &\quad + \sum_{j=0}^{n-1} (-1)^j \binom{n-1}{j} \frac{n}{4m(j+1)} I_1\left(\frac{1}{4m\beta(j+1)}\right). \end{aligned} \tag{18}$$

In this case, the bit error rate at all nodes is the same, which can be obtained by plugging (18) into (4) or (5). If we let $\beta = 1$, that is, the channel gains are modeled as zero mean, unit variance complex Gaussian random variables, the resulting expression reduces to expression (10) derived in [31].

V. Achievable Diversity Order

Showing that the full diversity order is achieved with the subset assignment criterion directly proves that the optimal assignment scheme achieves the full diversity as well. While the final expressions derived above are exact, they do not reveal the diversity order of the system. In this section, we derive an upper bound on P_e that proves that the maximum diversity order, which is n, is achieved. In order to achieve this goal, we simply assume that all the channel gains are modeled as zero mean, unit variance complex Gaussian random variables, i.e., symmetric channels, but this does not change the diversity order of the system over asymmetric channels, as demonstrated in [30].

With this assumption, the average bit error rate of all the links are the same. Thus, we simply use $P_{e,SR}$ to represent the bit error rate of all links. For $P_{e,S_i} = P_{e,D_i}$, we use P_e to represent the end-to-end bit error rate. To this end, we can upper bound P_e in (4) and (5) as

$$\begin{aligned} P_e &= 2\left(1 - P_{e,SR}\right)\left(1 - P_{e,SR}\right) P_{e,SR} \\ &\quad + \left[1 - 2P_{e,SR}\left(1 - P_{e,SR}\right)\right] P_{e,SR} \\ &\le 3P_{e,SR}. \end{aligned} \tag{19}$$

The last line is obtained by assuming that $0 \le P_{e,SR} << 1$, which is true in the practical SNR range. From (19), we know that to prove that P_e achieves full diversity order, it is sufficient to prove that $P_{e,SR}$ achieves full diversity.

Note that $P_{e,SR}$ can be expressed as

$$P_{e,SR} = \int_0^\infty Q\left(\sqrt{2\rho h}\right) f(h)\, dh, \tag{20}$$

where $f(h)$ is the pdf of $|h_{SR}|^2$ corresponding to the selected relay, which is given as [21]

$$\begin{aligned} f(h) &= n\left(4m - 1\right) e^{-h} \int_0^h e^{-(4m-1)\theta} \left(1 - e^{-4m\theta}\right)^{n-1} d\theta \\ &\quad + n e^{-4mh} (1 - e^{-4mh})^{n-1}. \end{aligned} \tag{21}$$

Using (20) and (21), we can express $P_{e,SR}$ as $P_{e,SR} = P_{e_1} + P_{e_2}$, where

$$P_{e_1} = \int_0^\infty Q\left(\sqrt{2\rho h}\right) \left[n e^{-4mh} (1 - e^{-4mh})^{n-1}\right] dh, \tag{22}$$

and

$$\begin{aligned} P_{e_2} &= \int_0^\infty Q\left(\sqrt{2\rho h}\right) \left(n\left(4m - 1\right) e^{-h}\right) \\ &\quad \cdot \left(\int_0^h e^{-(4m-1)\theta} \left(1 - e^{-4m\theta}\right)^{n-1} d\theta \right) dh. \end{aligned} \tag{23}$$

We now examine the behavior of the expressions of P_{e_1} and P_{e_2} in terms of the diversity order. Using Chernoff bound, we can upper bound P_{e_1} as shown in (24). Note that the last expression in (24) is actually the Beta function, given as [32]

$$B(x, y) = \int_0^1 t^{x-1} (1 - t)^{y-1} dt = \frac{\Gamma(x)\Gamma(y)}{\Gamma(x + y)},$$

$$P_{e_1} \leq \int_0^\infty \frac{1}{2}\left[ne^{-4mh}(1-e^{-4mh})^{n-1}\right]e^{-\rho h}dh = -\frac{n}{8m}\int_0^\infty e^{-\rho h}(1-e^{-4mh})^{n-1}de^{-4mh} = \frac{n}{8m}\int_0^1 t^{\frac{\rho}{4m}}(1-t)^{n-1}dt. \quad (24)$$

for $\mathrm{Re}\{x\} > 0$ and $\mathrm{Re}\{y\} > 0$, and $\Gamma(x)$ is the Gamma function. Armed with the above results, and when ρ is sufficiently large, we can express the last expression in (24) as

$$\begin{aligned} P_{e_1} &\leq \frac{n}{8m}B\left(\frac{\rho}{4m}+1, n\right) \\ &= \frac{n}{8m}\frac{\Gamma\left(\frac{\rho}{4m}+1\right)\Gamma(n)}{\Gamma\left(\frac{\rho}{4m}+1+n\right)} \\ &= \frac{n!}{8m}\left(\prod_{i=1}^{n}\left(\frac{\rho}{4m}+i\right)\right)^{-1} \\ &= O(\rho^{-n}), \end{aligned} \quad (25)$$

which suggests that the full diversity order is achieved.

Similarly, using Chernoff bound, we can upper bound P_{e_2} as

$$\begin{aligned} P_{e_2} &\leq \int_0^\infty \frac{1}{2}n(4m-1)e^{-(\rho+1)h} \\ &\quad \cdot \left(\int_0^h e^{-(4m-1)\theta}\left(1-e^{-4m\theta}\right)^{n-1}d\theta\right)dh \\ &= \frac{n(4m-1)}{2(1+\rho)}\int_0^\infty e^{-(4m+\rho)h}\left(1-e^{-4mh}\right)^{n-1}dh \\ &= \frac{n(4m-1)}{8m(1+\rho)}\int_0^1 t^{\frac{\rho}{4m}}(1-t)^{n-1}dt \\ &= \frac{(4m-1)\,n!}{8m(1+\rho)}\left(\prod_{i=1}^{n}\left(\frac{\rho}{4m}+i\right)\right)^{-1} \\ &= O\left(\rho^{-(n+1)}\right), \end{aligned} \quad (26)$$

which suggests that the diversity order of this term is $n+1$, which is one more than the maximum diversity order. Since the performance is dominated by the term with the lower diversity order, we conclude that the diversity order of the bit error rate with the subset assignment criterion is indeed n, which is the full diversity order. Consequently, the optimal assignment criterion achieves the full diversity order as well.

VI. Simulation Results

We present in this section some simulation results to validate the bit error rate expressions derived in the previous sections. Specifically, we confirm that both assignment criteria achieve the full diversity order. We also examine the degradation in performance due to using the subset assignment criterion as opposed to the optimal one. Throughout this section, we assume that all nodes use BPSK.

In Fig. 2, we compare our subset scheme with two other existing relay assignment schemes, which are random selection and sequential selection over symmetric channels. In random selection, relay assignment is randomly selected from the set Φ, which contains all the assignment permutations. It turns out that the performance of this scheme is the same as the case of one pair with one relay. In sequential selection, we first pick one relay and one pair by finding the largest value of $\boldsymbol{\gamma}_j^i$ in Φ, then remove this pair and this relay from Φ. The same thing repeats until all pairs have their corresponding selected relays. As such, all pairs have the same opportunity to be served by the best relay, the second best relay, etc., leading to equivalent performances among all of them. Furthermore, since the performance is dominated by the case when the pair is assigned last in the process, the overall diversity order of this scheme is $n-m+1$. That is, when the last pair is assigned a relay, only $n-m+1$ relays are left for assignment, hence the relays contribute only $n-m+1$ to the diversity order. For example, as shown in the figure, the diversity order is one for $m=3, n=3$ and two for $m=2,\ n=3$, whereas it is shown that our scheme achieves full diversity order, which is n.

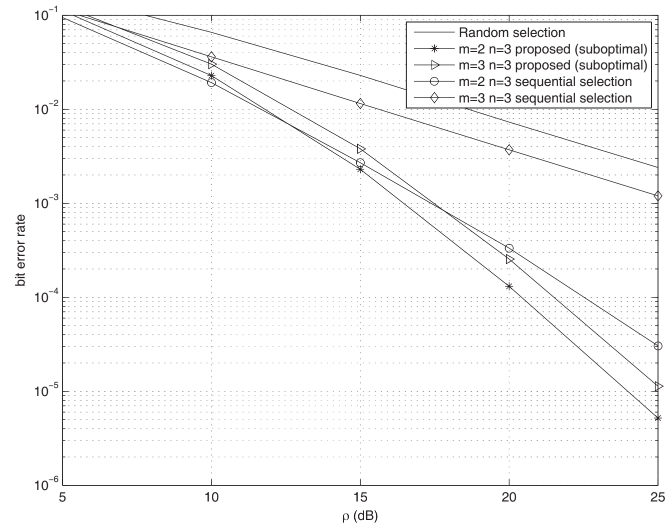

Fig. 2. Performance of the suboptimal assignment scheme, random selection and sequential selection (over symmetric channels).

In Fig. 3, we present the bit error rate performance for the following cases: $m=n=2$; $m=2$, $n=3$; and $m=n=3$ over symmetric channels. In all cases, we consider both the optimal and subset assignment criteria. For the $m=n=2$ case, as shown in the figure, the diversity is two and the performance is the same since both criteria are equivalent (as noted before). The diversity increases to three in the cases when $n=3$. In addition, we can see the degradation in SNR due to the subset assignment scheme, which is a little over 1 dB at bit error rate 1×10^{-5}. Finally, we observe that the performance of the optimal assignment criterion improves as m decreases from three to two, while the diversity order is

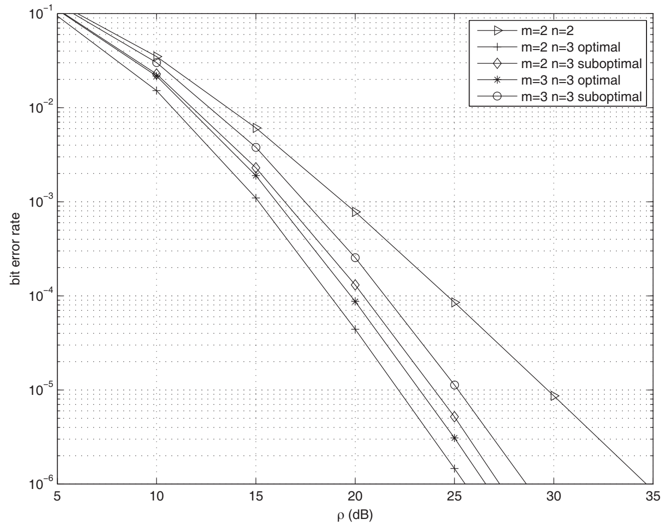

Fig. 3. Bit error rate performance comparison between the optimal and suboptimal assignment schemes for various m and n.

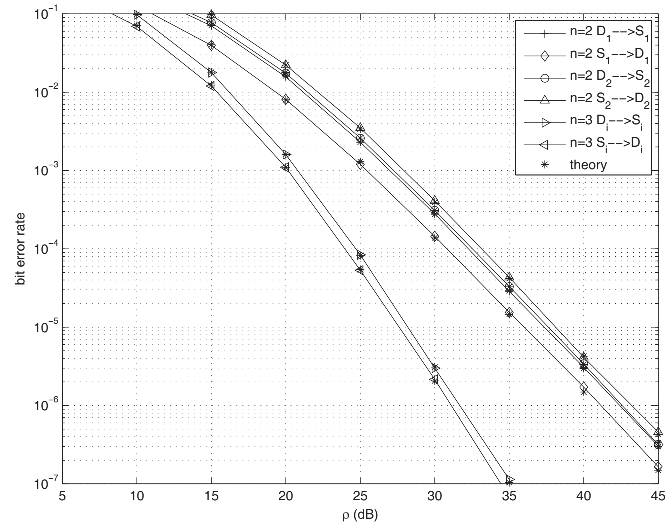

Fig. 5. Bit error rate performance (simulated and theoretical) of the suboptimal assignment scheme over asymmetric channels.

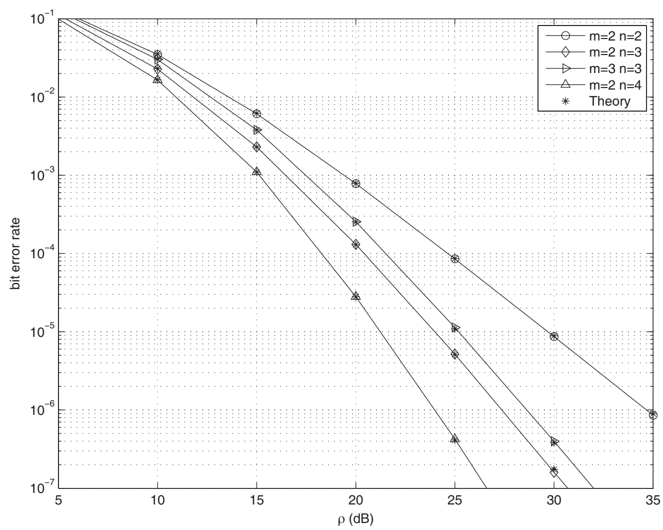

Fig. 4. Bit error rate performance (simulated and theoretical) of the suboptimal assignment scheme.

the same in both cases. This is attributed to the fact that when $m < n$, the number of ways the relays can be assigned to the m pairs is more, giving rise to the possibility of finding a better permutation.

In Fig. 4, we compare the simulated bit error rate to the theoretical expression derived in Section IV for symmetric channels. In our simulations, we set all channel variances to one. It is obvious that all the communication nodes have the same average bit error probability. In particular, we consider the cases: $m = 2,\ 3$ and $n = 2,\ 3,\ 4$. In all cases, we consider the subset assignment scheme. As shown in the figure, the performance improves as n increases. Also, the performance improves as m decreases while fixing n (similar to the observation in Fig. 3.) We can also see the perfect match between theory and simulations, which validates the derived bit error rate expression for symmetric channels.

In Fig. 5, we show the bit error performance of the subset assignment scheme for asymmetric channels. We consider two cases: $m = 2$ and $n = 2,\ 3$. To simplify the presentation, let $\boldsymbol{v}_j^i$ denote the set $\{E\left[\left|h_{S_iR_j}\right|^2\right],\ E\left[\left|h_{R_jS_i}\right|^2\right],\ E\left[\left|h_{D_iR_j}\right|^2\right],\ E\left[\left|h_{R_jD_i}\right|^2\right]\}$ where $E\left[\left|h_{S_iR_j}\right|^2\right]$ represents the variance of the channel coefficient of the $S_i - R_j$ link. The other terms are similarly defined. In the simulations, for the case $m = 2, n = 2$, we randomly set $\boldsymbol{v}_1^1 = \left(1,\ \frac{1}{8},\ \frac{1}{4},\ \frac{1}{2}\right)$, $\boldsymbol{v}_2^2 = \left(\frac{1}{12},\ 1,\ \frac{1}{3},\ \frac{1}{7}\right)$, $\boldsymbol{v}_2^1 = \left(\frac{1}{6},\ \frac{1}{14},\ \frac{1}{3},\ \frac{1}{2}\right)$, and $\boldsymbol{v}_1^2 = \left(\frac{1}{9},\ \frac{1}{5},\ \frac{1}{10},\ \frac{1}{9}\right)$. As such, all the nodes have different average bit error rates, which are displayed as four curves in the figure. It is shown from the curves that the full diversity order is achieved, which is $n = 2$ for all the nodes in the network. As for the case $m = 2, n = 3$, we set $\boldsymbol{v}_j^i = \left(\frac{1}{3},\ \frac{1}{4},\ \frac{1}{2},\ 1\right)$. In this case, since the channels are semi-symmetric, the average bit error rates are the same for the different pairs, hence there are only two curves for this case. As we expect, the link $S_i \longrightarrow D_i$ has a better performance than $D_i \longrightarrow S_i$ because the channel from the relay to D_i is better than that from the relay to S_i. In addition, we observe that full diversity order is achieved for both nodes, which is $n = 3$. In addition, we can also observe the perfect match between theory and simulations, which validates the bit error rate expression derived for asymmetric channels.

VII. Conclusions

We addressed in this paper relay assignment schemes for cooperative systems with multiple two-way relay channels cooperating through relays that employ network coding. We explored two assignment criteria: optimal and subset over asymmetric, semi-symmetric and symmetric channels. We derived closed-form expressions for the end-to-end bit error rate performance and showed that the full diversity order is achieved in all cases.

Throughout the paper, we assumed that a single relay helps up to one pair. This might pose some limitation from an implementation point of view. Instead, one might consider assigning one relay to multiple pairs at the same time. One way to achieve this is to use higher order modulation schemes at the relay nodes where the bits comprising a symbol correspond to different pairs. The challenge that comes to mind immediately, among others, would be to find the modulation size to use and how to assign the pairs to the relays. This will be tackled in future work. In addition, our proposed relay assignment schemes are centralized ones, which require significant overheads for large networks, Therefore, an interesting remaining topic to be studied is to find efficient distributed relay assignment schemes.

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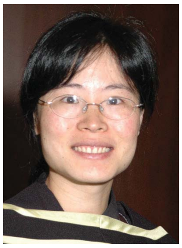

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