Performance Analysis of Relay Assignment Schemes for Cooperative Networks with Multiple Source-Destination Pairs

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***Abstract*—In this paper, we consider two relay assignment schemes for cooperative networks comprising multiple source-destination pairs. Both schemes are based on the max-min criterion and aim at achieving the maximum spatial diversity for all pairs. One scheme is used as a performance benchmark since it considers all possible relay assignment permutations and selects the best one. The other scheme, on the other hand, considers only a subset of those permutations and selects the best one. The advantages of the latter one is that it reduces the complexity of the assignment process, in addition to making the performance analysis tractable. We examine these schemes over asymmetric channels using M-ary phase shift keying signaling. We consider both amplify-and-forward (AF) and decode-and-forward (DF) relaying where we derive expressions for the end-to-end (E2E) symbol error rate (SER). In both cases, we show that the full spatial diversity is achieved. To account for error propagation in DF relaying, we adopt a threshold-based relaying scheme whereby the relays forward only bits that are deemed reliable and remain silent otherwise. We compare this scheme to Genie-aided relaying where the relays forward only correctly decoded bits. We analyze these two schemes and derive expressions for the E2E SER performance. We present several numerical examples that validate the analytical results.**

***Index Terms*—Amplify-and-forward, cooperative communication, decode-and-forward, error propagation, relay assignment.**

I. Introduction

COOPERATIVE communications has been shown to be an effective way to combat the adverse effects of fading channels [1]-[4]. Such technology can achieve the same spatial diversity that centralized multiple-input multiple-output (MIMO) systems offer, while alleviating most of the challenges arising in MIMO systems such as complexity and lack of flexibility. An active research area in cooperative communications is *selection diversity*, which aims at utilizing the system/network resources in a more efficient way [5]-[13]. Several relay selection schemes have been proposed in the literature, which are suitable for both decode-and-forward (DF) or amplify-and-forward (AF) relaying [15].

The authors in [5] propose a scheme where the relay that contributes the most to the received signal-to-noise ratio (SNR) is selected. It is shown that this scheme achieves full diversity. A selection scheme termed *nearest-neighbour relay selection* is proposed in [6], where the relay that is closest to the source is selected. The diversity order of this scheme with AF relaying is analyzed in [7], and is shown to achieve a diversity of one. A relay selection scheme based on the end-to-end channel quality for both AF and DF is proposed in [8], [9]. The authors show that using the best relay for cooperation could achieve the same diversity-multiplexing trade-off as that of the space-time coding scheme proposed in [16]. For this selection scheme, there are two main relay selection methods: Proactive and reactive opportunistic relaying [9].[1]. In proactive opportunistic relaying, the relay selection is based solely on the quality of the subchannels, which takes place before the source actually transmits its signal. Specifically, the relays are ordered according to their respective weakest subchannels, i.e., bottlenecks, and the one exhibiting the best bottleneck is chosen. In reactive opportunistic relaying, on the other hand, relay selection is performed after the source transmission over the first hop. That is, the selected relay is the one that has successfully decoded the source's message and whose relay-destination subchannel is the strongest.

Closed-form expressions for the outage and bit error probability of uncoded, threshold-based proactive opportunistic relaying and reactive opportunistic relaying are derived in [10]. It is also shown that the relative performance of the two relaying schemes is highly affected by the threshold. The diversity order of proactive opportunistic AF relaying without direct path is derived in [7], and it is shown that the full diversity is achieved, which is equal the number of relays. Closed-form expressions for the outage and bit error probability for proactive opportunistic AF relaying with a direct path between the source and destination can be found in [12], and for proactive opportunistic DF relaying in [13]. It is shown in both cases that the full diversity can be achieved. The outage probability and average channel capacity of reactive DF opportunistic relaying are derived in [14].

Most of the above works consider selecting the best relay,

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[1]Note that the authors in [8], [10] use opportunistic relaying to refer to proactive opportunistic relaying. On the other hand, in [10] and [11], the authors use selection cooperation to refer to reactive opportunistic relaying.

according to a certain criterion, to serve a pair of nodes in a network. Relay assignment for multiple pairs in relay networks is considered in [11], [17]-[18]. A relay assignment scheme based on the location of the relays is proposed in [17]. In [18], the authors propose an assignment scheme, which is based on maximizing the minimum capacity among all pairs. The authors focus on developing a polynomial time algorithm, which is able to offer a linear complexity for each iteration.

In this paper, we consider two relay assignment schemes for networks with multiple pairs, where the nodes of each pair are assumed to have a direct path between them. These schemes are solely based on the channel quality, which implies that the relay assignment is done prior to the actual transmission from the pairs. Accordingly, once a relay is assigned to a certain pair, that relay needs to decode only the message coming from its respective pair. In all schemes, we assume that a single relay is assigned to a single pair at any given time, suggesting that the number of relays should be at least as many as the number of pairs.[2] This is a realistic assumption because any node in the network can serve as a relay.[3]

In assigning the relays to the pairs, we first analyze the scheme that considers all possible permutations and picks the one that results in achieving the maximum spatial diversity for all pairs. We then propose a simplified scheme, which involves a search over only a subset of the possible permutations of assigning relays to the network pairs. This leads to tractability in the analysis and offers lower computational complexity. We examine both schemes with both AF and DF relaying over asymmetric Rayleigh fading channels with M-ary phase shift keying (MPSK). For AF, we derive a tight lower bound on the end-to-end (E2E) symbol error rate (SER). As for DF, we derive an exact expression for the E2E SER performance under the assumption that the relays forward only correctly decoded bits. In both cases, we show that the full spatial diversity is achieved, which equals the number of relays plus one (resulting from the direct path), for all pairs involved in the transmission. That is, all pairs achieve the same performance.

To account for error propagation in the DF relaying mode, we adopt threshold-based relaying where the assigned relay computes log-likelihood ratios (LLRs) for the received bits and subjects them to a threshold (as per [23], [24]). The bit whose LLR value exceeds the threshold is relayed (after making a hard decision on it); otherwise, the relay remains silent. We analyze this scheme and obtain an approximate expression for the E2E bit error rate (BER). We assume here binary phase shift keying (BPSK) since the analysis for MPSK proved to be difficult. We show that this scheme outperforms the conventional cyclic redundancy check (CRC) for all range of SNRs. It also outperforms the case when the relay forwards the bits without thresholding.

To the best of our knowledge, [11] is the only work that is directly related to what we are proposing here. There are, however, major differences between the schemes considered here and the ones in [11]. For instance, the schemes in [11] are based on reactive opportunistic relaying, that is, the relay is only chosen from the relays that have successfully decoded the received bits. As such, all relays have to attempt to decode all the messages that they receive before they are assigned. Also the relays need to send a message to the destination to indicate whether or not they have successfully decoded the message. This will consequently incur additional overhead and complexity. Furthermore, only the outage probability performance is considered in [11]. We remark that our relay assignment schemes reduce to the proactive opportunistic relaying scheme ([8], [9]) for networks with one pair and multiple relays. The performance of this scheme has been extensively studied in the literature for AF and DF relaying. As an example, the authors in [25] consider the proactive opportunistic relaying scheme over semi-symmetric channels, which is a special case of what is proposed in this paper. Another contribution of our paper to the proactive DF opportunistic relaying scheme is that we adopt LLR-threshold relaying to control error propagation, which is inherent in the relaying process.

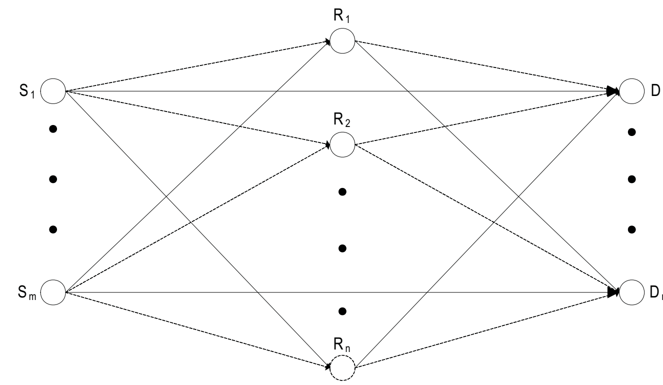

Fig. 1. System model.

The remainder of the paper is organized as follows. The system model is presented in Section II. In Section III, we present the relay assignment schemes analyzed in the paper. Performance analysis is carried out in Section IV. In Section V, we analyze the threshold-based relaying scheme. Several numerical examples and simulation results are given in Section VI, and Section VII concludes the paper.

II. SYSTEM MODEL

We consider the system model shown in Fig. 1, in which the network consists of m pairs and n relays where $n \geq m$. Each of the nodes is equipped with a single antenna and operates in a half-duplex mode. In the first time slot, the source of each pair transmits its signal, i.e., m nodes transmit simultaneously in the first time slot using frequency division multiple access (FDMA) [16]. Depending on the relaying strategy, the assigned relays cooperate in the second time slot (more on this below). We assume that a central controller in the network has the CSI of all the links.[4] Note that only one relay is assigned to each pair, and this assignment is done

[2] Assuming orthogonal channels, a single relay can also help multiple pairs while achieving the same bandwidth efficiency as the model adopted here, but the latter is obviously superior.

[3] The same system model is analyzed in [19] for DF relaying and when network coding is used at the relay nodes.

[4] 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. Such challenge can be addressed by employing a centralized or semi-distributed resource allocation scheme [20].

before actual transmission takes place. As such, each relay will have to decode only the signal coming from the pair it is assigned to. We also assume that there is a direct path between the nodes that comprise one pair, as shown in Fig. 1. Therefore, each destination receives two copies of the original signal, one from the corresponding source directly and one from the assigned relay.

The network subchannels[5] are assumed to experience independent, slow and frequency-nonselective Rayleigh fading. Let $h_{S_iR_j}$, $h_{R_jD_i}$ and $h_{S_iD_i}$ (for $i=1,\ldots,m,\ j=1,\ldots,n$) denote the fading coefficient between the ith source$-j$th relay, jth relay$-i$th destination and ith source$-i$th destination, respectively. The subchannels are assumed to be independent and *asymmetric*, i.e., all the subchannels have different average SNRs, which is the most general case. We also assume MPSK signaling throughout the paper (for the LLR-based relaying, we assume $M=2$, i.e., BPSK signaling).

Let $y_{S_iR_j}$ denote the received signal at the jth relay from the ith source, and $y_{S_iD_i}$ denote the received signal at the ith destination from the ith source, which are expressed, respectively, as $y_{S_iR_j}=\sqrt{\rho}h_{S_iR_j}x_{S_i}+n_{S_iR}$, and $y_{S_iD_i}=\sqrt{\rho}h_{S_iD_i}x_{S_i}+n_{S_iD_i}$, where x_{S_i} is the signal transmitted from the ith source (drawn from a MPSK signal constellation), and $n_{S_iR_j}$ is an additive white complex Gaussian noise (AWGN) sample corresponding to the ith source-jth relay subchannel, with zero mean and unit variance. $n_{S_iD_i}$ is similarly defined. As mentioned above, we consider in this paper three relaying schemes, namely, AF, genie-aided DF, and threshold-based DF relaying. Details of these schemes are given below.

A. AF Relaying

With AF relaying, each selected relay amplifies and forwards the signal without decoding. The relayed signal at the ith destination is then expressed as

$$y_{R_jD_i}=G_ih_{R_jD_i}y_{S_iR_j}+n_{R_jD_i},$$

where

$$G_i=\sqrt{\rho/\left(\left|h_{S_iR_j}\right|^2\rho+1\right)}$$

is the amplifying gain used at the jth relay. At the destination, the receiver combines the signals received over the two time slots via maximum ratio combining (MRC) as [26]

$$y_{S_iD_i}h^*_{S_iD_i}+y_{R_jD_i}\frac{h^*_{S_iR_j}h^*_{R_jD_i}G^*_i}{\left|h_{R_jD_i}\right|^2|G_i|^2+1}$$

Then a hard decision is made based on the MRC-combined signal.

B. Genie-aided DF Relaying

Genie-aided relaying implies that the selected relay cooperates only if the signal is decoded correctly at the relay; otherwise the relay remains silent. We use this scheme as a benchmark for the relaying scheme that we study in the next section.[6] The signal received from the selected relay at the ith destination is expressed as $y_{R_jD_i}=\sqrt{\rho}h_{R_jD_i}\hat{x}_{S_iR_j}+n_{R_jD_i}$, where $\hat{x}_{S_iR_j}$ is a hard decision made based on $y_{S_iR_j}h^*_{S_iR_j}$. Consequently, if the signal is decoded correctly at the relay, the MRC combined signal at the ith destination is expressed as $y_{R_jD_i}h^*_{R_jD_i}+y_{S_iD_i}h^*_{S_iD_i}$. This combined signal can then be used to make a hard decision on the transmitted symbol, denoted by $\hat{x}_{D_i}$.

C. LLR-based Relaying

In genie-aided relaying, the relay is assumed to know exactly when an error occurs, which is rather idealistic. In addition, when a CRC code is employed, it may not be efficient because in certain cases, a whole block of bits is discarded when even a single error occurs, resulting in a degradation in performance [27], [28]. As an alternative, the selected relay may compute an estimate of the received bit in the form of an LLR and subject this LLR value to a predetermined threshold. If the LLR value exceeds the threshold, the corresponding bit is deemed reliable, and a hard decision is made on it and is relayed; otherwise, the relay remains silent.

The LLR value can be computed as [23], [29]

$$\Lambda_{S_iR_j}=4\sqrt{\rho}\left(\left|h_{S_iR_j}\right|^2x+\Re e\left\{n_{S_iR_j}h^*_{S_iR_j}\right\}\right).$$

The optimal threshold for the LLR-based relaying is derived as [23], [24]

$$\Lambda_i=\ln\left(\frac{P_{e,P_i}-P_{e,S_iRD_i}}{P_{e,S_iD_i}}-1\right)$$

where $P_{e,S_iR_jD_i}$ represents the bit error rate of ideal relaying, P_{e,P_i} represents the bit error rate at the destination given that the relay forwarded a wrong bit to the destination, and P_{e,S_iD_i} represents the bit error rate at the destination without relaying. When $|\Lambda_{S_iR}|\geqslant\Lambda_i$, the relay forwards the received bit to the ith destination, and the received signal is expressed as

$$y_{R_jD_i}=\sqrt{\rho}h_{R_jD_i}\hat{x}_{S_iR_j}+n_{R_jD_i},$$

where

$$\hat{x}_{S_iR_j}=sign\left(\Re e\left\{y_{S_iR_j}h^*_{S_iR_j}\right\}\right).$$

Consequently, the final decoded bits using MRC at the ith destination is expressed as

$$\hat{x}_{D_i}=sign\left(\Re e\left\{y_{R_jD_i}h^*_{R_jD_i}+y_{S_iD_i}h^*_{S_iD_i}\right\}\right).$$

When $\left|\Lambda_{S_iR_j}\right|<\Lambda_i$, the relay remains silent. As such, the corresponding destination has only one copy of the signal, which was sent directly from the corresponding source. In this case, the final decoded bit is $\hat{x}_{D_i}=\text{sign}\left(\Re e\left\{y_{S_iD_i}h^*_{S_iD_i}\right\}\right)$.

III. Relay Assignment Criteria

The relay assignment schemes studied here are based on the max-min criterion. Such criterion obviously depends on the E2E instantaneous SNR between the pair nodes, which is determined by the subchannel instantaneous SNR, as well as the subchannels between the nodes themselves, namely, $\gamma_{S_iR_j}$, $\gamma_{R_jD_i}$ and $\gamma_{S_iD_i}$ (for $i=1,\ldots,m,\ j=1,\ldots,n$) where $\gamma_{S_iR_j}=\rho\left|h_{S_iR_j}\right|^2$. The E2E instantaneous SNR can be approximated as $\min\left\{\gamma_{S_iR_j},\gamma_{R_jD_i}\right\}+\gamma_{S_iD_i}$ for both AF

[5]A subchannel in this context refers to the link between any two nodes in the network.

[6]In practice, genie-aided relaying may be achieved by employing a CRC type code for channel coded networks.

and DF relaying [12], [13]. Involving the direct path in the relay assignment process complicates the analysis (more on this later.) As such, we discard the direct path in the relay assignment process; however, we emphasize here that the direct path is always present in the analysis and simulations throughout the paper.

In this section, we discuss two relay assignment criteria. The first criterion considers all possible permutations, and hence serves as a benchmark, whereas the second criterion limits the search to a subset of the available permutations.

A. Full-set Selection (FSS)

This selection scheme is introduced to benchmark the performance of all other schemes as it involves searching over all possible assignment permutations and selecting the best among the weakest links, i.e., max-min criterion. To simplify the notation, let γ_j^i denote the set $\{\gamma_{S_iR_j},\ \gamma_{R_jD_i}\}$, which is the set of the instantaneous SNRs between the jth relay and the nodes of the ith pair. Since there are two hops separating the end nodes in each pair, the weaker link is the one that dominates the E2E SER performance. Therefore, the relay assignment permutation that results in the best subchannel among the weakest ones is selected. We remark that one can also do the relay assignment for AF relaying based on the E2E SNR [5], [7].

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 ($2m$ of them since there are m pairs and each pair involves two 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 selected assignment, denoted by ϕ_{k^*}, has index k^*, and is obtained as

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

As an example, consider the case 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 γ_1^1, γ_2^2 and γ_3^3, respectively. Each of these elements represents two fading coefficients, as defined before, thus there are six fading coefficients comprising ϕ_1. Obviously, $\gamma_{1,\min}$ in (1) is the minimum of those six coefficients. Once the minimum of each row is obtained, the permutation corresponding to the largest is selected.

Since this assignment scheme is exhaustive, it suffers from high complexity. For example, when $n = m = 10$, there are $P_m^n = 3628800$ permutations to search over. In addition, when trying to find the statistics of the distribution of the best set, there is correlation between certain elements of Φ, which makes the performance analysis difficult. For instance, rows one and five (in Table I) are correlated since in both cases R_1 is assigned to the first pair. Such correlation makes it difficult to find a closed form expression for the probability density function (pdf) of the selected permutation. These reasons motivate us to consider a subset assignment scheme, described next, whereby the permutations considered are not correlated. Note that the fading coefficients are uncorrelated from a fading point of view, but correlation arises from the repeated elements when writing the max-min equation.

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

B. Subset Selection (SSS)

The objective here is to divide the set Φ into subsets such that correlation among the permutations within a subset is eliminated. (As an immediate consequence, the number of permutations to be examined is much less, resulting in a reduced complexity.) Then the best permutation within one subset (selected randomly) is selected. The number of subsets is $N = P_m^n/n$. 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.[7] 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

[7]It should be emphasized here that when $m = 1$, both assignment criteria are equivalent to the opportunistic relaying scheme proposed in [8]. Another special case is that, when $m = 2, n = 2$, FSS is the same as SSS.

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 the correlation among the permutations of a subset. This should be clear from Table I.

It should be noted here that only one subset needs to be established in practice since all subsets lead to the same performance, as will be shown later.

IV. Performance Analysis

In this section, we derive a lower bound on the SER performance for AF relaying. We also derive a closed-form expression for the SER for Genie-DF relaying. For both cases, since it is hard to deduce the achieved diversity order from the derived expressions, we derive an upper bound to show that the maximum diversity is achieved. For all cases, the SSS scheme is considered, and the direct path, albeit being present, is ignored in the assignment process.

A. AF Relaying

The instantaneous SNR of the weaker link of the two hops $\gamma_{i,\min}$ $(\gamma_{i,\min} = \min\{\gamma_{S_iR}, \gamma_{RD_i}\})$ is proved to be a tight upper bound of the equivalent one-hop instantaneous SNR [30]. Then, the E2E SNR of AF relaying can be expressed as $\gamma_{i,E2E} \leq \gamma_{i,\min} + \gamma_{S_iD_i}$. In [12] and [13], the authors adopt this idea to derive an expression for the BER for opportunistic relaying. Here we use this result to get an SER expression for the SSS relay assignment scheme.

The pdf of $\gamma_{i,\min}$ can be expressed as[8] [21]

$$
\begin{aligned}
f_{\gamma_{i,\min}}(\gamma) = & \sum_{j=1}^{n} \lambda_{ij}\left(\lambda_j - \lambda_{ij}\right) e^{-\lambda_{ij}\gamma} \\
& \cdot \int_0^{\gamma} \left[e^{-(\lambda_j-\lambda_{ij})\theta} \prod_{m\neq j}\left(1-e^{-\lambda_m\theta}\right)\right] d\theta \\
& + \sum_{j=1}^{n}\left[\lambda_{ij} e^{-\lambda_j\gamma}\prod_{m\neq j}\left(1-e^{-\lambda_m\gamma}\right)\right], \quad (2)
\end{aligned}
$$

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

[8]We remark that obtaining this pdf, while taking the direct path into consideration in the assignment process or considering all possible permutations, is not tractable statistically.

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

$$
f_{\gamma_{i,\min}}(\gamma) = \sum_{j=1}^{n}\sum_{\tau\in T_j^n} \operatorname{sign}(\tau)\lambda_{ij} e^{-(\lambda_j+\tau)\gamma}, \quad (3)
$$

for $m = 1$, and to

$$
\begin{aligned}
f_{\gamma_{i,\min}}(\gamma) = & \sum_{j=1}^{n}\sum_{\tau\in T_j^n} \frac{\operatorname{sign}(\tau)\lambda_{ij}\left(\lambda_j-\lambda_{ij}\right)}{\lambda_j-\lambda_{ij}+\tau} \\
& \cdot e^{-\lambda_{ij}\gamma}\left[1-e^{-(\lambda_j-\lambda_{ij}+\tau)\gamma}\right] \\
& + \sum_{j=1}^{n}\sum_{\tau\in T_j^n} \operatorname{sign}(\tau)\lambda_{ij} e^{-(\lambda_j+\tau)\gamma}, \quad (4)
\end{aligned}
$$

when $m \neq 1$, 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 $\operatorname{sign}(\tau)$ is the sign function [31]. That is,

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

The moment generating function (MGF) of γ can be calculated as [33]

$$
M_\gamma(s) = \int_0^\infty e^{-s\gamma} f_\gamma(\gamma)\, d\gamma. \quad (5)
$$

Now, plugging (3) and (4) into (5) and after some manipulations, we obtain

$$
M_{\gamma_{i,\min}}(s) = \sum_{j=1}^{n}\sum_{\tau\in T_j^n}\operatorname{sign}(\tau)\frac{\lambda_{ij}}{\lambda_j+\tau+s}, \quad (6)
$$

for $m = 1$, and

$$
\begin{aligned}
M_{\gamma_{i,\min}}(s) = & \sum_{j=1}^{n}\sum_{\tau\in T_j^n}\frac{\operatorname{sign}(\tau)\lambda_{ij}\left(\lambda_j-\lambda_{ij}\right)}{\lambda_j-\lambda_{ij}+\tau} \\
& \cdot\left(\frac{1}{\lambda_{ij}+s}-\frac{1}{\lambda_j+\tau+s}\right) \\
& + \sum_{j=1}^{n}\sum_{\tau\in T_j^n}\operatorname{sign}(\tau)\frac{\lambda_{ij}}{\lambda_j+\tau+s}, \quad (7)
\end{aligned}
$$

when $m \neq 1$. The pdf of $\gamma_{S_iD_i}$ corresponding to the ith source-destination direct link is given as

$$
f_{\gamma_{S_iD_i}}(\gamma) = \delta_i e^{-\gamma\delta_i}, \quad (8)
$$

where $\delta_i \triangleq \frac{1}{\overline{\gamma}_{S_iD_i}}$.

Plugging (8) into (5) yields $M_{\gamma_{S_iD_i}}(s) = \frac{\delta_i}{\delta_i+s}$. The MGF of $\gamma_{i,E2E}$ can be written as $M_{\gamma_{i,E2E}}(s) = M_{\gamma_{S_iD_i}}(s)\, M_{\gamma_{i,\min}}(s)$. Hence, when $m = 1$,

$$
M_{\gamma_{i,E2E}}(s) = \sum_{j=1}^{n}\sum_{\tau\in T_j^n}\frac{sign(\tau)\delta_i\lambda_{ij}}{\left(\lambda_j+\tau+s\right)\left(s+\delta_i\right)}, \quad (9)
$$

and

$$\begin{aligned} M_{\gamma_{i,E2E}}(s) &= \sum_{j=1}^{n}\sum_{\tau\in T_j^n}\frac{sign(\tau)\delta_i\lambda_{ij}\left(\lambda_j-\lambda_{ij}\right)}{\left(\lambda_j-\lambda_{ij}+\tau\right)\left(s+\delta_i\right)} \\ &\quad\cdot\left(\frac{1}{\lambda_{ij}+s}-\frac{1}{\lambda_j+\tau+s}\right) \\ &\quad+\sum_{j=1}^{n}\sum_{\tau\in T_j^n}\frac{sign(\tau)\delta_i\lambda_{ij}}{\left(\lambda_j+\tau+s\right)\left(s+\delta_i\right)}, \end{aligned} \tag{10}$$

when $m \neq 1$. Note that the E2E SER for MPSK can be expressed as [33]

$$P_e=\frac{1}{\pi}\int_0^{(M-1)\pi/M} M_\gamma\left(\frac{g_{PSK}}{\sin^2\theta}\right)d\theta. \tag{11}$$

Now plugging (9) and (10) into (11) and after some manipulations, the E2E SER can be lower bounded as

$$\begin{aligned} P_{i,E2E} &\geq \sum_{j=1}^{n}\sum_{\tau\in T_j^n}\frac{sign(\tau)\delta_i\lambda_{ij}}{\delta_i-\lambda_j-\tau} \\ &\quad\cdot\left[\frac{I_1\left(\frac{\sin^2(\pi/M)}{\lambda_j+\tau}\right)}{\lambda_j+\tau}-\frac{I_1\left(\frac{\sin^2(\pi/M)}{\delta_i}\right)}{\delta_i}\right], \end{aligned} \tag{12}$$

when $m=1$, where

$$\begin{aligned} I_1(c) &\triangleq \frac{M-1}{M}\left\{1-\sqrt{\frac{c}{1+c}}\left(\frac{M}{(M-1)\pi}\right)\right. \\ &\quad\left.\cdot\left[\frac{\pi}{2}+\tan^{-1}\left(\sqrt{\frac{c}{1+c}}\cot\left(\frac{\pi}{M}\right)\right)\right]\right\}, \end{aligned}$$

and

$$\begin{aligned} P_{i,E2E} \geq &\sum_{j=1}^{n}\sum_{\tau\in T_j^n}\frac{sign(\tau)\delta_i\lambda_{ij}}{\delta_i-\lambda_j-\tau} \\ &\cdot\left[\frac{1}{\lambda_j+\tau}I_1\left(\frac{\sin^2(\pi/M)}{\lambda_j+\tau}\right)-\frac{1}{\delta_i}I_1\left(\frac{\sin^2(\pi/M)}{\delta_i}\right)\right] \\ &-\sum_{j=1}^{n}\sum_{\tau\in T_j^n}sign(\tau)\frac{\delta_i\lambda_{ij}\left(\lambda_j-\lambda_{ij}\right)}{\left(\lambda_j-\lambda_{ij}+\tau\right)}\frac{1}{\delta_i-\lambda_j-\tau} \\ &\cdot\left(\frac{1}{\lambda_j+\tau}I_1\left(\frac{\sin^2(\pi/M)}{\lambda_j+\tau}\right)-\frac{1}{\delta_i}I_1\left(\frac{\sin^2(\pi/M)}{\delta_i}\right)\right) \\ &+\sum_{j=1}^{n}\sum_{\tau\in T_j^n}sign(\tau)\frac{\delta_i\lambda_{ij}\left(\lambda_j-\lambda_{ij}\right)}{\left(\lambda_j-\lambda_{ij}+\tau\right)}\frac{1}{\delta_i-\lambda_{ij}} \\ &\cdot\left(\frac{1}{\lambda_{ij}}I_1\left(\frac{\sin^2(\pi/M)}{\lambda_{ij}}\right)-\frac{1}{\delta_i}I_1\left(\frac{\sin^2(\pi/M)}{\delta_i}\right)\right), \end{aligned} \tag{13}$$

when $m \neq 1$ and $\delta_i \neq \lambda_{ij}$ [33], where

$$\begin{aligned} I_2(c) &\triangleq \frac{M-1}{M}-\frac{1}{\pi}\sqrt{\frac{c}{1+c}} \\ &\quad\cdot\left\{\left(\frac{\pi}{2}+\tan^{-1}\alpha\right)\left[1+\frac{1}{2(1+c)}\right]\right. \\ &\quad\left.+\frac{1}{2(1+c)}\sin\left(\tan^{-1}\alpha\right)\cos\left(\tan^{-1}\alpha\right)\right\}, \end{aligned}$$

and $\alpha \triangleq \sqrt{\frac{c}{1+c}}\cot\frac{\pi}{M}$.

While the expressions in (12) and (13) give a lower bound on the SER performance, they do not yield the diversity order achieved. This motivates us to derive an upper bound on the SER performance, which clearly shows that a diversity of $n+1$ is achieved. The derivation is given in *Appendix I*.

B. Genie-aided DF Relaying

The E2E SER of the genie-aided DF relaying can be expressed as

$$P_{e,i}=P_{e,S_iR_j}P_{e,S_iD_i}+(1-P_{e,S_iR_j})P_{e,S_iR_jD_i}, \tag{14}$$

where P_{e,S_iR_j} and P_{e,S_iD_i} are the probabilities of making an error over the S_i-R_j link and S_i-D_i link, respectively. $P_{e,S_iR_jD_i}$ is the SER of ideal relaying assuming the relay forwards all symbols correctly. The expression of P_{e,S_iD_i} is given as

$$P_{e,S_iD_i}=I_1\left(\frac{\sin^2(\pi/M)}{\delta_i}\right). \tag{15}$$

We now find expressions for P_{e,S_iR_j} and $P_{e,S_iR_jD_i}$ so that we can obtain closed-form expressions for $P_{e,i}$ defined by (14). To be able to do so, we need to find the pdf of the random variables involved, namely, $\gamma_{S_iR_j}$ and $\gamma_{R_jD_i}$. Although these variables are independent and different (on average), their pdfs will be similar where we can use one expression to express the two pdfs. As such, to make the presentation simpler, we denote these variables by γ_{ik} for $k=1,2$ where $\gamma_{i1}=\gamma_{S_iR}$ and $\gamma_{i2}=\gamma_{R_jD_i}$.

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

$$\begin{aligned} f_{\gamma_{ik}}(\gamma) &= \sum_{j=1}^{n}\lambda_{ij,k}\left(\lambda_j-\lambda_{ij,k}\right)e^{-\lambda_{ij,k}\gamma} \\ &\quad\cdot\int_0^{\gamma}\left[e^{-(\lambda_j-\lambda_{ij,k})\theta}\prod_{m\neq j}\left(1-e^{-\lambda_m\theta}\right)\right]d\theta \\ &\quad+\sum_{j=1}^{n}\left[\lambda_{ij,k}e^{-\lambda_j\gamma}\prod_{m\neq j}\left(1-e^{-\lambda_m\gamma}\right)\right], \end{aligned} \tag{16}$$

where $\lambda_{ij,1} \triangleq \frac{1}{\overline{\gamma}_{S_iR_j}}$ and $\lambda_{ij,2} \triangleq \frac{1}{\overline{\gamma}_{R_jD_i}}$ (for $i = 1,\ldots,m,\ j=1,\ldots,n$) and $\lambda_j \triangleq \sum_{i=1}^{m}\left(\lambda_{ij,1}+\lambda_{ij,2}\right)$. $\overline{\gamma}_{S_iR_j}=\rho E\left[\left|h_{S_iR_j}\right|^2\right]$ 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

$$\begin{aligned} f_{\gamma_{ik}}(\gamma) &= \sum_{j=1}^{n}\sum_{\tau\in T_j^n}\mathrm{sign}(\tau)\frac{\lambda_{ij,k}\left(\lambda_j-\lambda_{ij,k}\right)}{\lambda_j-\lambda_{ij,k}+\tau} \\ &\quad\cdot e^{-\lambda_{ij,k}\gamma}\left[1-e^{-(\lambda_j-\lambda_{ij,k}+\tau)\gamma}\right] \\ &\quad+\sum_{j=1}^{n}\sum_{\tau\in T_j^n}\mathrm{sign}(\tau)\lambda_{ij,k}e^{-(\lambda_j+\tau)\gamma}, \end{aligned} \tag{17}$$

Substituting (17) into (5) and (11) and after some manipulations, P_{e,S_iR} can be expressed as

$$\begin{aligned} P_{e,S_iR} &= \sum_{j=1}^{n}\sum_{\tau\in T_j^n}\text{sign}(\tau)\frac{\lambda_{ij,1}(\lambda_j-\lambda_{ij,1})}{\lambda_j-\lambda_{ij,1}+\tau} \\ &\quad\cdot\left[\frac{I_1\left(\frac{\sin^2(\pi/M)}{\lambda_{ij,1}}\right)}{\lambda_{ij,1}}-\frac{I_1\left(\frac{\sin^2(\pi/M)}{\lambda_j+\tau}\right)}{\lambda_j+\tau}\right] \\ &\quad+\sum_{j=1}^{n}\sum_{\tau\in T_j^n}\frac{\text{sign}(\tau)\lambda_{ij,1}I_1\left(\frac{\sin^2(\pi/M)}{\lambda_j+\tau}\right)}{\lambda_j+\tau}. \end{aligned} \tag{18}$$

For ideal relaying, the E2E SNR can be expressed as $\gamma_{S_iRD_i}=\gamma_{RD_i}+\gamma_{S_iD_i}$. Following steps similar to those that led to (13), P_{e,S_iRD_i} can be expressed as

$$\begin{aligned} P_{e,S_iRD_i} &= \sum_{j=1}^{n}\sum_{\tau\in T_j^n}sign(\tau)\frac{\delta_i\lambda_{ij,2}}{\delta_i-\lambda_j-\tau} \\ &\cdot\left[\frac{1}{\lambda_j+\tau}I_1\left(\frac{\sin^2(\pi/M)}{\lambda_j+\tau}\right)-\frac{1}{\delta_i}I_1\left(\frac{\sin^2(\pi/M)}{\delta_i}\right)\right] \\ &-\sum_{j=1}^{n}\sum_{\tau\in T_j^n}sign(\tau)\frac{\delta_i\lambda_{ij,2}\left(\lambda_j-\lambda_{ij,2}\right)}{\left(\lambda_j-\lambda_{ij,2}+\tau\right)\left(\delta_i-\lambda_j-\tau\right)} \\ &\cdot\left[\frac{1}{\lambda_j+\tau}I_1\left(\frac{\sin^2(\pi/M)}{\lambda_j+\tau}\right)-\frac{1}{\delta_i}I_1\left(\frac{\sin^2(\pi/M)}{\delta_i}\right)\right] \\ &+\sum_{j=1}^{n}\sum_{\tau\in T_j^n}sign(\tau)\frac{\delta_i\lambda_{ij,2}\left(\lambda_j-\lambda_{ij,2}\right)}{\left(\lambda_j-\lambda_{ij,2}+\tau\right)\left(\delta_i-\lambda_{ij,2}\right)} \\ &\cdot\left[\frac{1}{\lambda_{ij,2}}I_1\left(\frac{\sin^2(\pi/M)}{\lambda_{ij,2}}\right)-\frac{1}{\delta_i}I_1\left(\frac{\sin^2(\pi/M)}{\delta_i}\right)\right] \end{aligned} \tag{19}$$

when $\delta_i\neq\lambda_{ij,2}$. An expression for $P_{e,i}$ is obtained by using (15), (18) and (19) in (14). This resulting expression, similar to the AF relaying case, does not yield the diversity order achieved. To reveal this diversity, one can follow the approach given in [36] to show that a diversity of $n+1$ is achieved in this case.

V. Threshold-Based Relaying

With LLR-based relaying, the selected relay computes the LLR values of the received bits and compares them to a pre-determined threshold. If the LLR value is larger than the threshold, a hard decision on the corresponding bit is made and then is relayed to the corresponding destination. Otherwise, the relay remains silent. One can also use SNR-based relaying, but the LLR-based relaying has been shown to outperform SNR-based relaying [23], [24], [28].

Let x be the transmitted signal from a source to a relay.[9] The relay then computes the corresponding LLR value as $\Lambda_{S_iR_j}=4\sqrt{\rho}\left(\left|h_{S_iR_j}\right|^2x+\Re e\left\{n_{S_iR_j}h^*_{S_iR_j}\right\}\right)$ [23], [29]. Also, let $Z_i=\frac{\left|\Lambda_{S_iR_j}\right|}{4}$, then the bit error probability of the S_i-R_j link in terms of Z_i is derived as $P_{e,S_iR_j}=1/\left(1+e^{4Z_i}\right)$ [29]. The average E2E BER is given by

$$P_e=P_{e,S_iD_i}(1-P_{T_i})+P_{e,S_iR_jD_i}\left(1-P_{e|T_i}\right)+P_{e,P_i}P_{e|T_i} \tag{20}$$

[9]BPSK modulation is assumed in this section.

where $P_{e,S_iR_jD_i}$ represents the bit error rate of ideal relaying, P_{e,P_i} represents the bit error rate at the destination given that the relay forwards a wrong bit to the destination and P_{e,S_iD_i} represents the bit error rate at the destination without relaying. $1-P_{T_i}$ represents the probability that the absolute value of the LLR is less than the threshold and $P_{e|T_i}$ represents the probability that the absolute value of LLR is greater than threshold Λ_i while an error occurs at the relay.

All the terms in (20) have been derived in [23] and [24] for the case of only one pair and one relay. As such, these expressions need to be re-derived for our system model. We first derive the pdf of Z_i which is needed to derive $1-P_{T_i}$ and $P_{e|T_i}$ in (20). The expressions for P_{e,S_iD_i} and $P_{e,S_iR_jD_i}$ are already given in (15), (19), respectively. In this part, $M=2$ since BPSK modulation is assumed. Extending the analysis to MPSK proved difficult due to the difficulty in obtaining the pdf of the LLR values.

To get the pdf of Z_i, we first need to derive the pdf of $Y_i=\frac{\Lambda_{S_iR}}{4}$. Following the approach of [29], the pdf of Y_i is $f_{Y_i}(y_i)=f^{(1)}_{Y_i}(y_i)+f^{(2)}_{Y_i}(y_i)$, where

$$f^{(1)}_{Y_i}(y_i)=\int_0^\infty\frac{e^{-\frac{(y_i-x\rho)^2}{x\rho}}}{\sqrt{\pi x\rho}}\sum_{j=1}^{n}\sum_{\tau\in T_j^n}\text{sign}(\tau)\lambda_{ij}e^{-(\lambda_j+\tau)x}dx,$$

$$\begin{aligned} f^{(2)}_{Y_i}(y_i) &= \int_0^\infty\frac{e^{-\frac{(y_i-x\rho)^2}{x\rho}}}{\sqrt{\pi x\rho}}\sum_{j=1}^{n}\sum_{\tau\in T_j^n}\text{sign}(\tau)\frac{\lambda_{ij}\left(\lambda_j-\lambda_{ij}\right)}{\lambda_j-\lambda_{ij}+\tau} \\ &\quad\cdot e^{-\lambda_{ij}\gamma}\left[1-e^{-(\lambda_j-\lambda_{ij}+\tau)x}\right]dx, \end{aligned}$$

where $\lambda_{ij}\triangleq\frac{1}{E\left[\left|h_{S_iR_j}\right|^2\right]}$ (for $i=1,\dots,m,\ j=1,\dots,n$) and $\lambda_j\triangleq\sum_{i=1}^m\left(\frac{1}{E\left[\left|h_{S_iR_j}\right|^2\right]}+\frac{1}{E\left[\left|h_{R_jD_i}\right|^2\right]}\right)$. Correspondingly, we write the pdf of Z_i as

$$f_{Z_i}(z_i)=f^{(1)}_{Z_i}(z_i)+f^{(2)}_{Z_i}(z_i), \tag{21}$$

where $f^{(1)}_{Z_i}(z_i)$ and $f^{(2)}_{Z_i}(z_i)$ correspond to $f^{(1)}_{Y_i}(y_i)$ and $f^{(2)}_{Y_i}(y_i)$, respectively. We now derive an expression for $f^{(1)}_{Y_i}(y_i)$.

Letting $b=\sqrt{x}$ and carrying out the integration, we can write $f^{(1)}_{Y_i}(y_i)$ as

$$f^{(1)}_{Y_i}(y_i)=\sum_{j=1}^{n}\sum_{\tau\in T_j^n}\frac{\text{sign}(\tau)\lambda_{ij}}{\sqrt{\rho\left(\rho+\lambda_j+\tau\right)}}e^{2y_i-2|y_i|\sqrt{\frac{\rho+\lambda_j+\tau}{\rho}}}, \tag{22}$$

where we use the equality $\int_0^\infty e^{-ax^2-\frac{b}{x^2}}dx=\frac{1}{2}\sqrt{\frac{\pi}{a}}e^{-2\sqrt{ab}}$ [22], [29]. The cdf $F^{(1)}_{Z_i}(z_i)=\int_{-z_i}^{z_i}f^{(1)}_{Y_i}(y_i)dy_i$, can be derived as

$$\begin{aligned} &F^{(1)}_{Z_i}(z_i) \\ &= \sum_{j=1}^{n}\sum_{\tau\in T_j^n}\frac{\text{sign}(\tau)\lambda_{ij}\left[1-e^{-2z_i\left(\sqrt{1+\left(\lambda_j+\tau\right)\rho^{-1}}+1\right)}\right]}{2\left[\left(\lambda_j+\tau+\rho\right)+\sqrt{\rho\left(\lambda_j+\tau+\rho\right)}\right]} \\ &\quad+\sum_{j=1}^{n}\sum_{\tau\in T_j^n}\frac{\text{sign}(\tau)\lambda_{ij}\left[1-e^{-2z_i\left(\sqrt{1+\left(\lambda_j+\tau\right)\rho^{-1}}-1\right)}\right]}{2\left[\left(\lambda_j+\tau+\rho\right)-\sqrt{\rho\left(\lambda_j+\tau+\rho\right)}\right]} \end{aligned} \tag{23}$$

Therefore, $f^{(1)}_{Z_i}(z_i)=\frac{dF^{(1)}_{Z_i}(z_i)}{dz_i}$ can be derived as

$$f^{(1)}_{Z_i}(z_i)=\sum_{j=1}^{n}\sum_{\tau\in T_j^n}\frac{\mathrm{sign}(\tau)\lambda_{ij}\left(1+e^{4z_i}\right)}{\sqrt{\rho\left(\lambda_j+\tau+\rho\right)}}e^{-2\left(\sqrt{1+(\lambda_j+\tau)\rho^{-1}}+1\right)z_i}. \tag{24}$$

Using similar steps, we can write $f^{(2)}_{Z_i}(z_i)$ as

$$\begin{aligned} f^{(2)}_{Z_i}(z_i) \;=\; & \sum_{j=1}^{n}\sum_{\tau\in T_j^n}\frac{\mathrm{sign}(\tau)\lambda_{ij}\left(\lambda_{ij}-\lambda_j\right)}{\lambda_j-\lambda_{ij}+\tau} \\ & \cdot\left[\frac{\left(1+e^{4z_i}\right)}{\sqrt{\rho\left(\lambda_j+\tau+\rho\right)}}e^{-2\left(\sqrt{1+(\lambda_j+\tau)\rho^{-1}}+1\right)z_i}\right. \\ & \left.-\frac{\left(1+e^{4z_i}\right)}{\sqrt{\rho\left(\lambda_{ij}+\rho\right)}}e^{-2\left(\sqrt{1+\lambda_{ij}\rho^{-1}}+1\right)z_i}\right]. \end{aligned} \tag{25}$$

Substituting (24) and (25) into (21), we get the pdf of Z_i. Now that we have this pdf, we can derive an expression for $1-P_{T_i}$ as

$$\begin{aligned} 1-P_{T_i} &= \int_0^{\frac{\Lambda_i}{4}} f_{Z_i}(z_i)dz_i \\ &= \sum_{j=1}^{n}\sum_{\tau\in T_j^n}\frac{\mathrm{sign}(\tau)\lambda_{ij}\left(\lambda_j-\lambda_{ij}\right)}{\lambda_j-\lambda_{ij}+\tau} \\ &\quad\cdot\left\{\frac{1-e^{-2\left(\sqrt{1+\lambda_{ij}\rho^{-1}}+1\right)\frac{\Lambda_i}{4}}}{2\left[\lambda_{ij}+\rho+\sqrt{\rho\left(\lambda_{ij}+\rho\right)}\right]}\right. \\ &\quad\left.+\frac{1-e^{-2\left(\sqrt{1+\lambda_{ij}\rho^{-1}}-1\right)\frac{\Lambda_i}{4}}}{2\left[\lambda_{ij}+\rho-\sqrt{\rho\left(\lambda_{ij}+\rho\right)}\right]}\right\} \\ &\quad+\sum_{j=1}^{n}\sum_{\tau\in T_j^n}\mathrm{sign}(\tau)\lambda_{ij}\left(1-\frac{\lambda_j-\lambda_{ij}}{\lambda_j-\lambda_{ij}+\tau}\right) \\ &\quad\cdot\left\{\frac{1-e^{-2\left(\sqrt{1+(\lambda_j+\tau)\rho^{-1}}+1\right)\frac{\Lambda_i}{4}}}{2\left[(\lambda_j+\tau+\rho)+\sqrt{\rho\left(\lambda_j+\tau+\rho\right)}\right]}\right. \\ &\quad\left.+\frac{1-e^{-2\left(\sqrt{1+(\lambda_j+\tau)\rho^{-1}}-1\right)\frac{\Lambda_i}{4}}}{2\left[(\lambda_j+\tau+\rho)-\sqrt{\rho\left(\lambda_j+\tau+\rho\right)}\right]}\right\}, \end{aligned} \tag{26}$$

and an expression for $P_{e|T_i}$ as

$$\begin{aligned} P_{e|T_i} &= \int_{\frac{\Lambda_i}{4}}^{\infty} P_{e,S_iR}f_{Z_i}(z_i)dz_i \\ &= \sum_{j=1}^{n}\sum_{\tau\in T_j^n}\frac{\mathrm{sign}(\tau)\frac{\lambda_{ij}\tau}{\lambda_j-\lambda_{ij}+\tau}e^{-\left(\sqrt{1+(\lambda_j+\tau)\rho^{-1}}+1\right)\frac{\Lambda_i}{2}}}{2\left[\lambda_j+\tau+\rho+\sqrt{\rho\left(\lambda_j+\tau+\rho\right)}\right]} \\ &\quad+\sum_{j=1}^{n}\sum_{\tau\in T_j^n}\frac{\mathrm{sign}(\tau)\lambda_{ij}\left(\lambda_j-\lambda_{ij}\right)e^{-\left(\sqrt{1+\lambda_i\rho^{-1}}+1\right)\frac{\Lambda_i}{2}}}{2\left(\lambda_j-\lambda_{ij}+\tau\right)\left[\rho+\lambda_{ij}+\sqrt{\rho\left(\rho+\lambda_{ij}\right)}\right]}. \end{aligned}$$

As for P_{e,P_i}, it is difficult to get an exact closed-form expression for it, but we approximate it as [34] $P_{e,P_i}\approx\frac{\overline{\gamma}_{RD_i}}{\overline{\gamma}_{RD_i}+\overline{\gamma}_{S_iD_i}}$, where $\overline{\gamma}_{RD_i}$ can be calculated as

$$\overline{\gamma}_{RD_i}=\int_0^{\infty}\gamma f_{\gamma_{ik}}(\gamma)\,d\gamma. \tag{27}$$

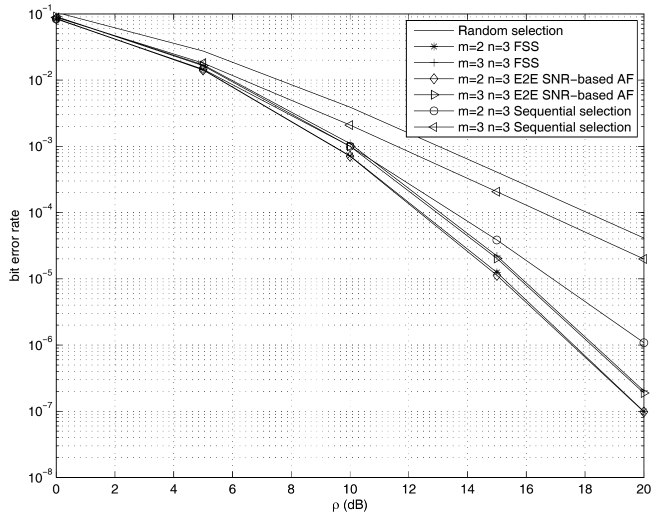

Fig. 2. Performance of FSS, random selection and sequential selection.

Plugging (17) into (27) and after some manipulations, $\overline{\gamma}_{RD_i}$ can be expressed as

$$\begin{aligned} \overline{\gamma}_{RD_i} \;=\; & \sum_{j=1}^{n}\sum_{\tau\in T_j^n}\frac{\mathrm{sign}(\tau)\lambda_{ij,2}\left(\lambda_j-\lambda_{ij,2}\right)}{\lambda_j-\lambda_{ij,2}+\tau} \\ & \cdot\left[\frac{1}{\lambda_{ij,2}^2}-\frac{1}{\left(\lambda_j+\tau\right)^2}\right] \\ & +\sum_{j=1}^{n}\sum_{\tau\in T_j^n}\frac{\mathrm{sign}(\tau)\lambda_{ij,2}}{\left(\lambda_j+\tau\right)^2}. \end{aligned} \tag{28}$$

After obtaining expressions for all the terms in (20), we get the E2E BER expression of the LLR-based relaying for the SSS assignment scheme. Although we only analyze the performance of the LLR-based relaying for SSS, this relaying scheme can apply to FSS in the same way. In addition, when $m=1$, our scheme reduces to the opportunistic relaying scheme proposed in [8].

VI. Simulation Results

We present in this section some simulation results to validate the theoretical expressions derived in the previous sections. In all simulations, unless otherwise mentioned, the subchannels are assumed to be independent and asymmetrical, and QPSK modulation is used.

A. AF Relaying

In Fig. 2, we compare the FSS scheme with three other relay assignment schemes, which are random selection, sequential selection and E2E SNR-based selection. All the channels are assumed to have the same average channel gains, i.e., symmetrical, which are modeled as zero mean, unit variance complex Gaussian random variables. BPSK modulation is used here. In random selection, relay assignment is done randomly from the set Φ, which contains all the assignment permutations. The performance of this scheme is the same as the case of one pair with one relay, which is expected. In sequential selection, we first pick out one relay and one pair

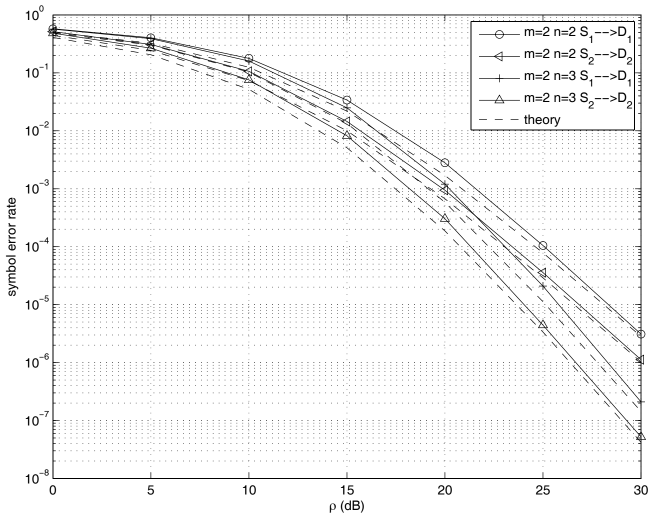

Fig. 3. Symbol error rate performance (theory and simulation) of SSS with AF relaying.

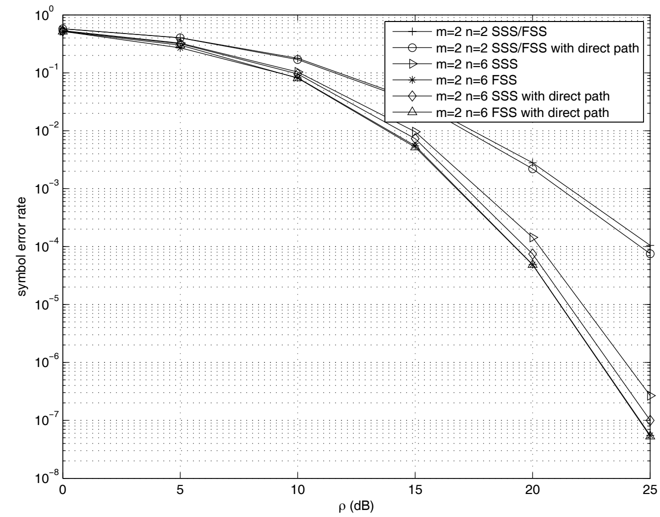

Fig. 4. Symbol error rate (simulation) comparison between SSS, FSS, with AF relaying.

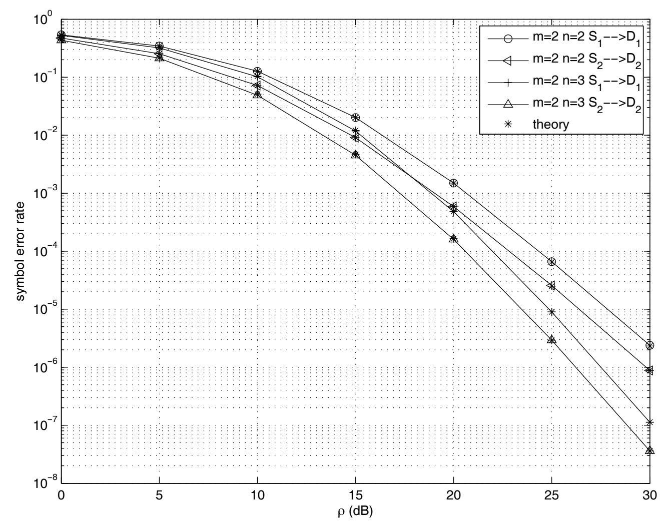

Fig. 5. Symbol error rate performance (theory and simulation) of Genie-DF relaying.

by finding the largest value of γ_j^i in Φ, then remove this pair and this relay from Φ. The same thing repeats until all the pairs have their corresponding selected relays. As such, all pairs have equal opportunities to be served by the best relay, the second best relay, etc., leading to equivalent performances among all of them. This is true because the subchannels are independent and a new relay assignment is done for every new set of channel realizations. Furthermore, since the performance in dominated by the case when the pair is assigned last in the process, the overall diversity of this scheme is $n-m+2$. 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, and the additional single diversity comes from the direct path. For example, as shown in the figure, the diversity is two for $m=3, n=3$ and three for $m=2, n=3$. It also shows that the FSS scheme achieves full diversity, which is $n+1$, similar to the diversity of the E2E SNR-based scheme with the latter being slightly superior [7].

In Fig. 3, we compare the simulated SER performance to the lower bound derived in (13) for the SSS scheme. To simplify the presentation, let υ_j^i denote the set $\{E[|h_{S_iR_j}|^2],\ E[|h_{R_jD_i}|^2]\}$ where $E[|h_{S_iR_j}|^2]$ represents the variance of the channel coefficients of the $S_i - R_j$ link. The other terms are similarly defined. In our simulations, for $m=2, n=2$, we randomly set $\upsilon_1^1 = \left(\frac{1}{7},\ \frac{1}{8}\right)$, $\upsilon_2^2 = \left(\frac{1}{3},\ \frac{1}{5}\right)$, $\upsilon_2^1 = \left(\frac{1}{4},\ \frac{1}{9}\right)$, and $\upsilon_1^2 = \left(\frac{1}{2},\ \frac{1}{6}\right)$. As for $m=2, n=3$, we set $\upsilon_3^1 = \left(\frac{1}{9},\ \frac{1}{6}\right)$, $\upsilon_3^2 = \left(1, \frac{1}{5}\right)$. The other items are the same as the case of $m=2, n=2$. It is shown that the lower bound is quite tight. In addition, it is shown in the figure that the full diversity of $n+1$ is achieved.

In Fig. 4, we present the SER performance of the FSS and SSS for the following cases: $m=2, n=2, 6$. The channel setting of $m=2, n=2$ is the same as Fig. 3. As for the case $m=2, n=6$, we set $\upsilon_4^1 = \left(\frac{1}{6}, 1\right)$, $\upsilon_4^2 = \left(\frac{1}{2}, \frac{1}{4}\right)$, $\upsilon_5^1 = \left(\frac{1}{7}, \frac{1}{8}\right)$, $\upsilon_5^2 = \left(\frac{1}{3}, \frac{1}{5}\right)$, $\upsilon_6^1 = \left(\frac{1}{8}, \frac{1}{3}\right)$, $\upsilon_6^2 = \left(1, \frac{1}{5}\right)$. The other items are the same as the case of $m=2, n=2$. For $m=n=2$, as shown in the figure, the diversity order is three for all the schemes and the performance of FSS is the same as SSS, since both criteria are equivalent. The diversity order increases to seven for all schemes for $n=6$. We also compare in Fig. 4 the E2E SER performance of the FSS and SSS schemes with and without the direct path being considered in the assignment process. For the case with direct path, the parameters γ_j^i in Φ are replaced by $\min\left\{\gamma_{S_iR_j}, \gamma_{R_jD_i}\right\} + \gamma_{S_iD_i}$ to take the information of the direct path into consideration. As expected, ignoring the direct path in the assignment process results in some degradation in the performance. For instance, the performance degrades by about 0.5 dB at SER 10^{-6} for the SSS scheme when the direct path is ignored. However, there is almost no degradation when the FSS scheme is used.

B. Genie-aided DF Relaying

In Fig. 5, we compare the simulated SER with the theoretical one for the genie-aided relaying scheme presented in Section IV-B. The channel setting is the same as that in Fig.

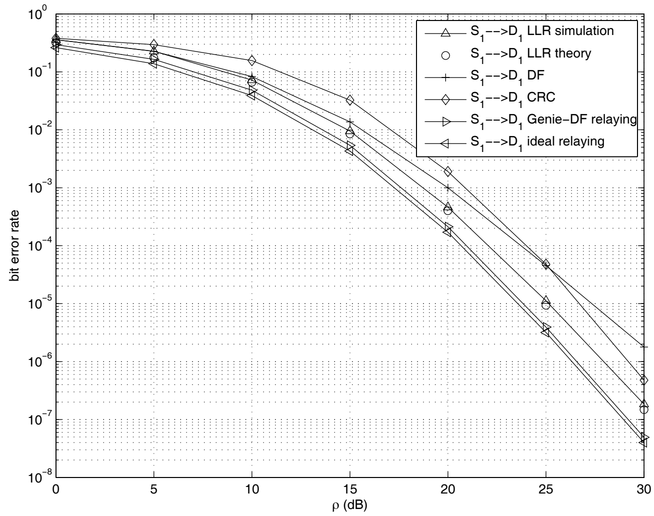

Fig. 6. Comparison of different relaying schemes for $m = 2, n = 3$ $(S_1 - D_1)$.

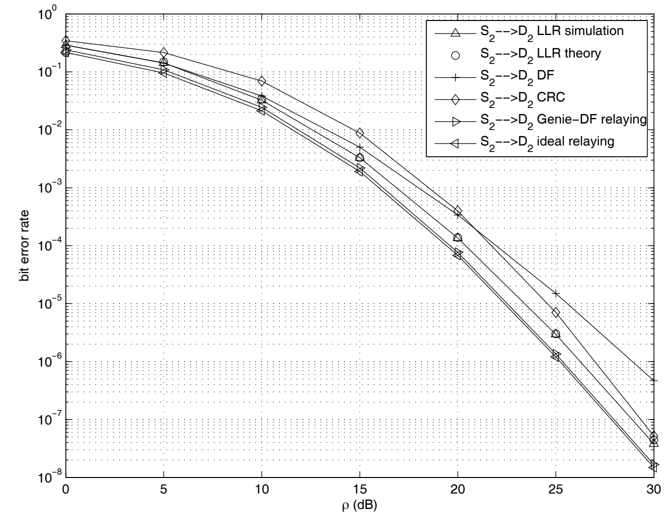

Fig. 7. Comparison of different relaying schemes for $m = 2, n = 3$ $(S_2 - D_2)$.

3. We can see the perfect match between the theoretical and simulation results. As shown in the figures, the performance improves as n increases, as expected. Also the performance improves as m decreases while fixing n. In addition, it is shown in the figure that the full diversity of $n+1$ is achieved in this case too.

C. LLR-based DF Relaying

In Fig. 6, we compare the simulation results of LLR-threshold relaying with the theoretical ones for $m = 2, n = 3$ (for pair $S_1{-}D_1$). The channels are the same as Fig. 5. Here we use the optimum threshold given in [23] and [24]. As shown in the figure, the simulation results agree with the theoretical results. In addition, we compare the performance of LLR-based thresholding relaying with other relaying schemes, including DF, CRC, Genie-DF relaying and ideal relaying. For DF relaying, the relay always forwards the decoded bits to the destination, whereas for CRC relaying, the relay only forwards the correctly decoded frames. Note that, although the system is uncoded, i.e., no channel coding is used, we assume that a frame of 100 bits see the same fade, and if there is one or more bits in error, the whole frame is discarded. From the figure, we can see that DF relaying suffers a diversity loss. In addition, both CRC and LLR-threshold based relaying achieve significant improvements in the end-to-end BER, while the latter is superior for all range of SNR shown in the figure. The performance loss of Genie-DF relaying is about 0.4 dB at BER 10^{-6} as compared to ideal relaying. Similar results with similar observations for pair $S_2{-}D_2$ are reported in Fig. 7.

VII. Conclusions

In this paper, we considered relay assignment schemes for relay networks comprising multiple source-destination pairs. We examined two assignment schemes, one based on searching over all possible assignment permutations, and another based on searching over only a subset of the possible permutations. We considered AF and DF relaying with MPSK modulation, and LLR-based relaying with BPSK relaying (over asymmetric channels.) For all cases, we have derived expressions for the symbol/bit error rate and showed that all relaying schemes achieved the maximum diversity available, which is $n+1$. We also compared the proposed assignment schemes with two well-studied assignment schemes, namely, random selection and sequential selection and demonstrated the superiority of the proposed schemes.

A Proof of the Diversity of AF Relaying

In this appendix, we prove that the expressions in (12) and (13) have diversity $n+1$. In particular, we derive an upper bound on the E2E SER performance and show that the maximum diversity is achieved. In order to achieve this goal, we simply assume symmetric channels because this assumption does not change the results for asymmetric channels [35]. The exact E2E SER of AF relaying can be expressed as $P_e = \int_0^\infty \int_0^\infty Q\left(\sqrt{2\rho(u+y)}\right) f(u)\, f(y)\, du dy$, where $u = \frac{|h_{SR}|^2 |h_{RD}|^2}{|h_{SR}|^2 + |h_{RD}|^2 + \rho^{-1}}$ and $y = |h_{SD}|^2$. Using Chernoff bound, we can upper bound P_e as [7]

$$P_e \leq P_{e_1} + P_{e_2}, \tag{29}$$

where $P_{e_1} = \frac{1}{2}\int_{\rho^{-1}}^\infty e^{-\frac{\rho x}{4}} f(x)\, dx \int_0^\infty e^{-\rho y} f(y)\, dy$, $P_{e_2} = \frac{1}{2}\int_0^{\rho^{-1}} f(x)\, dx \int_0^\infty e^{-\rho y} f(y)\, dy$. Note that $x = \min\left\{|h_{SR}|^2,\ |h_{RD}|^2\right\}$. Using the pdf of y, $f(y) = e^{-y}$, in the expressions of P_{e_1} and P_{e_2}, and carrying out the integration, these expressions can be expressed as $P_{e_1} = \frac{1}{2(\rho+1)}\int_{\rho^{-1}}^\infty e^{-\frac{\rho x}{4}} f(x)\, dx$ and $P_{e_2} = \frac{1}{2(\rho+1)}\int_0^{\rho^{-1}} f(x)\, dx$. We now examine the behavior of P_{e_1} and P_{e_2} in terms of the diversity order. The pdf of x can be written from (2) as

$$f(x) = 2n\,(2m-2)\, e^{-2x} \int_0^x e^{-(2m-2)\theta} \left(1 - e^{-2m\theta}\right)^{n-1} d\theta \\ + 2ne^{-2mx}(1 - e^{-2mx})^{n-1}.$$

Substituting $f(x)$ in P_{e_1}, we can express it as $P_{e_1} = P_{e_{11}} + P_{e_{12}}$, where

$$P_{e_{11}} = \frac{n}{\rho+1}\int_{\rho^{-1}}^{\infty} e^{-\frac{\rho x}{4}}\left[e^{-2mx}(1-e^{-2mx})^{n-1}\right]dx$$

$$\begin{aligned}P_{e_{12}} &= \frac{2n\,(2m-2)}{2(\rho+1)}\int_{\rho^{-1}}^{\infty} e^{-\frac{\rho x}{4}} \\ &\quad\cdot\left[e^{-2x}\int_0^x e^{-(2m-2)\theta}\left(1-e^{-2m\theta}\right)^{n-1}d\theta\right]dx,\end{aligned}$$

Now we can upper bound $P_{e_{11}}$ as

$$\begin{aligned}P_{e_{11}} &\le \frac{1}{2(\rho+1)}\int_0^{\infty} e^{-\frac{\rho x}{4}}\left[2ne^{-2mx}(1-e^{-2mx})^{n-1}\right]dx \\ &= \frac{n}{2m(\rho+1)}B\left(\frac{\rho}{8m}+1,n\right) \\ &= \frac{n}{2m(\rho+1)}\left(\prod_{i=1}^{n}\left(\frac{\rho}{8m}+i\right)\right)^{-1} = O(\rho^{-(n+1)}),\end{aligned} \quad (30)$$

where $B(x,y)$ in (30) is the Beta function given as [22] $B\left(x,y\right) = \int_0^1 t^{x-1}\left(1-t\right)^{y-1}dt$. In addition, $P_{e_{12}}$ can be upper bounded as

$$\begin{aligned}P_{e_{12}} &\le \frac{2n\,(2m-2)}{2(\rho+1)}\int_0^{\infty} e^{-\frac{\rho x}{4}} \\ &\quad\cdot\left[e^{-2x}\int_0^x e^{-(2m-2)\theta}\left(1-e^{-2m\theta}\right)^{n-1}d\theta\right]dx \\ &= \frac{n\,(2m-2)}{4(1+\rho)^2}\int_0^{\infty} e^{-\left(2m+\frac{\rho}{4}\right)x}\left(1-e^{-2mx}\right)^{n-1}dx \\ &= O(\rho^{-(n+2)}).\end{aligned} \quad (31)$$

The last two lines of (31) follow steps similar to that of (30). Plugging (30) and (31) into the expression of P_{e_1}, we can conclude that P_{e_1} has diversity $n+1$. Plugging the pdf of x into P_{e_2}, we can write it as $P_{e_2} = P_{e_{21}} + P_{e_{22}}$, where $P_{e_{21}} = \frac{1}{2(\rho+1)}\int_0^{\rho^{-1}} 2ne^{-2mx}(1-e^{-2mx})^{n-1}dx$, and

$$\begin{aligned}P_{e_{22}} &= \frac{1}{2(\rho+1)}\int_0^{\rho^{-1}} 2n\,(2m-2)\,e^{-2x} \\ &\quad\cdot\int_0^x e^{-(2m-2)\theta}\left(1-e^{-2m\theta}\right)^{n-1}d\theta dx.\end{aligned}$$

We can upper bound $P_{e_{21}}$ as

$$\begin{aligned}P_{e_{21}} &\le \frac{n}{(\rho+1)}\int_0^{\rho^{-1}}(1-e^{-2m\rho^{-1}})^{n-1}dx \\ &= \frac{n}{\rho(\rho+1)}(1-e^{-2m\rho^{-1}})^{n-1} = O(\rho^{-(n+1)}).\end{aligned} \quad (32)$$

In the same way, we can upper bound $P_{e_{22}}$ as

$$\begin{aligned}P_{e_{22}} &= \frac{n\,(2m-2)}{(\rho+1)}\int_0^{\rho^{-1}} e^{-2x}\int_0^x e^{-(2m-2)\theta}\left(1-e^{-2m\theta}\right)^{n-1}d\theta dx \\ &\le \frac{n\,(m-1)}{(\rho+1)}\int_0^{\rho^{-1}}\left(1-e^{-2m\rho^{-1}}\right)^{n-1}dx \\ &= \frac{n\,(m-1)}{\rho(\rho+1)}\left(1-e^{-2m\rho^{-1}}\right)^{n-1} = O(\rho^{-(n+1)}).\end{aligned} \quad (33)$$

Substituting (32) and (33) in P_{e_2}, we conclude that P_{e_2} has diversity $n+1$. Since both P_{e_1} and P_{e_2} achieve full diversity, we conclude from (29) that the SSS scheme with AF relaying achieves diversity $n+1$. We remark that [7] gives the diversity order analysis for opportunistic AF relaying without direct path for networks with a single source-destination pair and multiple relays. As such, the results reported in [7] can be considered as a special case of the results reported here.

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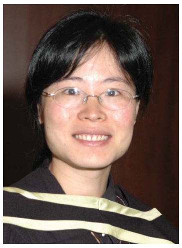

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