Opportunistic Source/Destination Cooperation in Cooperative Diversity Networks

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***Abstract*—In this paper, we combine opportunistic transmission and source/destination cooperation in a decode-and-forward (DF)-based two-hop cooperative diversity network consisting of multiple source-destination pairs and a single relay. Firstly, we consider a special scenario with two source-destination pairs. For this network, there are two possible strategies in each hop: no-cooperation or cooperation. Considering the combination of the two strategies in two cascaded hops, we investigate four different end-to-end transmission strategies, and we find that the four strategies complement one another depending on channel conditions in terms of outage performance. To maximize the mutual information, we propose an optimum joint selection of source-destination pair and end-to-end transmission strategy. Then we show that the optimum joint selection scheme can be simplified without loss of outage performance, and derive its exact outage probability in closed-form. Secondly, we generalize the proposed transmission strategy into a scenario with multiple source-destination pairs. For this network, we first propose an optimum end-to-end transmission strategy to maximize the mutual information, then a suboptimum end-to-end transmission strategy to reduce the signaling overhead and computational complexity. For the suboptimum strategy, we derive the outage probability and diversity order.**

***Index Terms*—Cooperative diversity network, decode-and-forward (DF), destination cooperation, opportunistic transmission, outage probability, source cooperation.**

I. Introduction

COOPERATIVE diversity has recently received considerable attention because it can attain broader coverage range and mitigate channel impairments by relaying signals in a network [1], [2]. One of the most well-known cooperative strategies is *decode-and-forward* (DF) relaying where each relay terminal detects the incoming signal and retransmits the detected symbol. There have been a lot of research activities on the DF relaying because it can easily be combined with channel codes and incorporated into network protocols. In many applications of cooperative diversity networks, there might be multiple source-destination pairs and multiple relays [3]–[6]. Many of the works have focused on relaying techniques such as beamforming at relays [3], [4], or relay selection [5], [6].

Recently, to improve the performance of a network with *multiple* source-destination pairs, some researchers have studied cooperation among multiple sources, which is referred to as "source cooperation" [7], [8], and cooperation among multiple destinations, which is referred to as "destination cooperation" [7]–[10]. All those works assumed that the direct-paths from multiple sources to multiple destinations were strong enough to be practically utilized, and thus, they did not considered the adoption of any *relay* terminals [7]–[10]. In many scenarios such as shadowed urban cellular channels or obstructed in buildings, however, direct-paths might be too weak to be practically utilized due to path attenuation and/or shadow fading. Furthermore, a weak direct-path is very difficult to be actually exploited because synchronization is extremely difficult in practical systems. In such scenarios, therefore, it should be a more practical and reasonable approach to adopt *relaying* techniques. To the best of our knowledge, however, there has been no work which has tried to investigate source cooperation and/or destination cooperation with *relay* terminals.[1]

On the other hand, *opportunistic transmission* has also been considered as an attractive technique in time-varying channels [11], [12]. Opportunistic transmission exploits time-varying channel fluctuations by selecting a single best user associated with the best channel gain at a given instant. Recently, many researchers have studied opportunistic transmission in cooperative diversity networks [13]–[21]. Bletsas *et al.* proposed opportunistic relay selection based on the "max-min" criterion [13], and they also proved the proposed scheme was outage optimal [14]. Gündüz *et al.* considered an opportunistic DF protocol where a relay retransmitted a symbol only if the symbol was correctly detected at the relay [15]. Zou *et al.* considered an opportunistic amplify-and-forward protocol for a source-destination pair with a relay where the relay retransmitted the incoming signal only if the channel from the source to the relay was not in outage [16]. To the best of our knowledge, however, there has been no prior work that *combined* opportunistic transmission and source/destination cooperation, each of which individually has a potential to improve the performance.

In this paper, we combine source/destination cooperation

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[1] In the literature, communications with relay terminals have been widely studied. Furthermore, the utilization of relay terminals is adopted in many standards such as Long Term Evolution (LTE)-Advanced and mobile Worldwide Interoperability for Microwave Access (WiMAX), based on IEEE802.16j mobile multihop relay (MMR) networks.

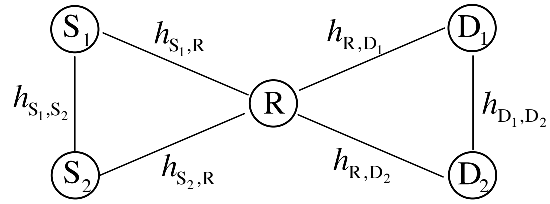


Fig. 1. System model for a cooperative diversity network consisting of two source-destination pairs and a relay without any direct-path from sources to destinations.

and opportunistic transmission in a DF-based *relaying* network. Specifically, we consider a network consisting of multiple source-destination pairs and a *single* relay, where there is *no* end-to-end direct-path from sources to destinations. Note that in our system model, multiple source-destination pairs share a *single* relay terminal. Although the possibility of *multiple* relays has been widely considered in the literature under the assumption that any mobile terminal may serve as a relay, there are actually some obstacles for such approach in practical systems. For example, frequency/time synchronization across the multiple relays becomes very difficult for non-stationary relay terminals due to the mobility, (fast) time-varying channels, and different distances from the source to the relays.[2] In many practical applications, therefore, one powerful stationary relay terminal may be considered as a more feasible and reasonable solution. For instance, in the next generation cellular network standard *Long Term Evolution* (*LTE*)-*Advanced*, a typical scenario is that one powerful stationary relay terminal is used in each cell.[3]

In this paper, we firstly consider a network with two source-destination pairs in Fig. 1, which will be generalized to multiple source-destination pairs. The network of Fig. 1 can be considered as a two-hop system without any end-to-end direct-path: the first hop is from two sources to the relay and the second hop is from the relay to two destinations. For each hop, there are two possible strategies: no-cooperation *or* cooperation. Considering the combination of the two strategies in two cascaded hops, we investigate four different end-to-end transmission strategies, and we demonstrate that the four transmission strategies have different outage performance and complement one another depending on channel conditions. To maximize the mutual information, therefore, we *jointly* determine *both* a best source-destination pair out of two source-destination pairs *and* a best end-to-end transmission strategy out of the four possible end-to-end transmission strategies. As a result, we propose an optimal joint selection of source-destination pair and end-to-end transmission strategy. Then we show that the optimum joint selection scheme can be simplified without loss of outage performance, and derive its exact outage probability.

Secondly, we generalize the proposed transmission strategy into a network with multiple source-destination pairs. We first propose an optimum end-to-end transmission strategy to maximize the mutual information. Due to the high signaling overhead as well as high computational complexity, it is extremely difficult to implement the optimum strategy as is in practical systems. In order to reduce the signaling overhead and computational complexity, we then propose a suboptimum end-to-end transmission strategy on a basis of group-based partition method. For the suboptimum strategy, we derive the outage probability and diversity order.

The remainder of this paper is organized as follows. In Section II, we describe the system model. In Section III, we consider four different end-to-end transmission strategies for two source-destination pairs. In Section IV, we propose an optimum joint selection scheme for two source-destination pairs. Then we show that the optimum joint selection scheme can be simplified without loss of outage performance, and we derive its exact outage probability. In Section V, we propose optimum and suboptimum end-to-end transmission strategies for multiple source-destination pairs. In Section VI, we present simulation results. Finally, conclusions are drawn in Section VII.

Notation: We use $U := V$ to denote that U, by definition, equals V, and we use $U =: V$ to denote that V, by definition, equals U. For a random variable W, $f_W(\cdot)$ denotes its probability density function (PDF). For terminals X, Y, and Z, $\mathcal{L}(X \to Y)$ denotes a signal path from X to Y; $\mathcal{L}(X \to Y \to Z)$ denotes a signal path from X via Y to Z; and $\mathcal{L}(X \xrightarrow{\to \mathrm{Y} \to} Z)$ denotes a combination of two signal paths $\mathcal{L}(X \to Z)$ and $\mathcal{L}(X \to Y \to Z)$. Finally, $x \sim \mathcal{CN}(m, \Omega)$ indicates that x is a circularly symmetric complex-valued Gaussian random variable with mean m and variance Ω.

II. System Description

In this section, we first describe the system model, and then we present the mutual information for the first and second hops.

A. System Model

Consider a cooperative diversity network consisting of L source-destination pairs and one relay, where each terminal has a single antenna and operates in a half-duplex mode. We use S_l, D_l, and R to denote the l-th source, the l-th destination, and the relay, respectively, where $l = 1, \cdots, L$. We suppose S_l intends to send data to D_l *only*. The end-to-end direct-paths from sources to destinations are not considered assuming the distances between the end terminals are very long and/or there are some obstacles between the end terminals.[4] The complex channel coefficient from S_l to R is denoted by $h_{\mathrm{S}_l,\mathrm{R}}$; the complex channel coefficient from R to D_l is denoted by $h_{\mathrm{R},\mathrm{D}_l}$; the complex inter-source channel coefficient between S_l and S_k is denoted by $h_{\mathrm{S}_l,\mathrm{S}_k}$; and the complex inter-destination channel coefficient between D_l and D_k is denoted by $h_{\mathrm{D}_l,\mathrm{D}_k}$, where $l, k = 1, \cdots, L$ and $k \neq l$. We assume that the inter-source and inter-destination channels are reciprocal, and that all the channel coefficients are fixed over channel coherence

[2]Furthermore, the multiple distinct relay terminals use their own distinct oscillators. Therefore, across the relay terminals, there exist carrier frequency offsets due to clock drifts resulting from inherent offsets in practical oscillator crystals [22].

[3]In LTE-Advanced, "Type 1" relay, which is one powerful stationary relay terminal, creates a separate cell distinct from the donor cell.

[4]In this case, there is no practically meaningful performance gain even if we add the weak direct-paths.

time with $h_{\mathrm{S}_l,\mathrm{R}} \sim \mathcal{CN}(0,\Omega_{\mathrm{S}_l,\mathrm{R}})$, $h_{\mathrm{R},\mathrm{D}_l} \sim \mathcal{CN}(0,\Omega_{\mathrm{R},\mathrm{D}_l})$, $h_{\mathrm{S}_l,\mathrm{S}_k} \sim \mathcal{CN}(0,\Omega_{\mathrm{S}_l,\mathrm{S}_k})$, and $h_{\mathrm{D}_l,\mathrm{D}_k} \sim \mathcal{CN}(0,\Omega_{\mathrm{D}_l,\mathrm{D}_k})$. The noise associated with every channel is modeled as a mutually independent additive white Gaussian noise (AWGN) with zero mean and unit variance. We let $\gamma_{\mathrm{S}_l,\mathrm{R}}$, $\gamma_{\mathrm{R},\mathrm{D}_l}$, $\gamma_{\mathrm{S}_l,\mathrm{S}_k}$, and $\gamma_{\mathrm{D}_l,\mathrm{D}_k}$ denote the instantaneous signal-to-noise ratios (SNRs) of the link from S_l to R, the link from R to D_l, the link from S_l to S_k, and the link from D_l to D_k, respectively, where $\gamma_{\mathrm{S}_l,\mathrm{R}} = \mathcal{P}|h_{\mathrm{S}_l,\mathrm{R}}|^2$, $\gamma_{\mathrm{R},\mathrm{D}_l} = \mathcal{P}|h_{\mathrm{R},\mathrm{D}_l}|^2$, $\gamma_{\mathrm{S}_l,\mathrm{S}_k} = \mathcal{P}|h_{\mathrm{S}_l,\mathrm{S}_k}|^2$, and $\gamma_{\mathrm{D}_l,\mathrm{D}_k} = \mathcal{P}|h_{\mathrm{D}_l,\mathrm{D}_k}|^2$ with the transmission power $\mathcal{P}$ at each terminal. We let $\bar{\gamma}_{\mathrm{S}_l,\mathrm{R}}$, $\bar{\gamma}_{\mathrm{R},\mathrm{D}_l}$, $\bar{\gamma}_{\mathrm{S}_l,\mathrm{S}_k}$, and $\bar{\gamma}_{\mathrm{D}_l,\mathrm{D}_k}$ denote the average SNRs associated with $\gamma_{\mathrm{S}_l,\mathrm{R}}$, $\gamma_{\mathrm{R},\mathrm{D}_l}$, $\gamma_{\mathrm{S}_l,\mathrm{S}_k}$, and $\gamma_{\mathrm{D}_l,\mathrm{D}_k}$, respectively, where $\bar{\gamma}_{\mathrm{S}_l,\mathrm{R}} = \mathcal{P}\Omega_{\mathrm{S}_l,\mathrm{R}}$, $\bar{\gamma}_{\mathrm{R},\mathrm{D}_l} = \mathcal{P}\Omega_{\mathrm{R},\mathrm{D}_l}$, $\bar{\gamma}_{\mathrm{S}_l,\mathrm{S}_k} = \mathcal{P}\Omega_{\mathrm{S}_l,\mathrm{S}_k}$, and $\bar{\gamma}_{\mathrm{D}_l,\mathrm{D}_k} = \mathcal{P}\Omega_{\mathrm{D}_l,\mathrm{D}_k}$.

The network we consider is a two-hop system without any end-to-end direct-path: the first hop is from L sources to the relay, and the second hop is from the relay to L destinations. In the following, we present the mutual information for each hop.

B. Mutual Information for First Hop

In this subsection, we investigate the mutual information in the first hop from L sources to the relay. In the first hop, multiple sources can cooperate with one another, which will be referred to as "source-cooperation." Suppose M sources out of L sources are involved in the source-cooperation, where $1 \leq M \leq L$. As a special case, when $M = 1$, there exist only a direct transmission from the transmitting source to the relay, which will be referred to as "no-source-cooperation." Without loss of generality, we assume S_l is the transmitting source and other $M-1$ sources relay the transmitted signal in the order $\mathrm{S}_{i_1}, \mathrm{S}_{i_2}, \cdots, \mathrm{S}_{i_{M-1}}$. This scenario can be represented by a row vector of M sources $[\mathrm{S}_l, \mathrm{S}_{i_1}, \mathrm{S}_{i_2}, \cdots, \mathrm{S}_{i_{M-1}}] =: \mathcal{C}_\mathrm{S}(l)$. At the first time slot, S_l transmits its own signal, which is received by R and $\{\mathrm{S}_{i_m}\}_{m=1}^{M-1}$. At the second time slot, S_{i_1} relays the transmitted signal, which is received by R and $\{\mathrm{S}_{i_m}\}_{m=2}^{M-1}$. At the third time slot, S_{i_2} relays the transmitted signal. In this manner, all the $M-1$ sources relay the transmitted signal.

We now consider the mutual information at the i_m-th relaying terminal S_{i_m} for $m = 1, \cdots, M-1$. At the first relaying terminal S_{i_1}, the mutual information $I([\mathrm{S}_l, \mathrm{S}_{i_1}])$ is involved only with a direct-path $\mathcal{L}(\mathrm{S}_l \rightarrow \mathrm{S}_{i_1})$. Therefore, $I([\mathrm{S}_l, \mathrm{S}_{i_1}])$ is given by

$$I([\mathrm{S}_l, \mathrm{S}_{i_1}]) = \log_2(1 + \gamma_{\mathrm{S}_l,\mathrm{S}_{i_1}}). \tag{1}$$

At the second relaying terminal S_{i_2}, the mutual information $I([\mathrm{S}_l, \mathrm{S}_{i_1}, \mathrm{S}_{i_2}])$ is involved with two signal paths: a direct-path $\mathcal{L}(\mathrm{S}_l \rightarrow \mathrm{S}_{i_2})$ and a relay-path $\mathcal{L}(\mathrm{S}_l \rightarrow \mathrm{S}_{i_1} \rightarrow \mathrm{S}_{i_2})$. Therefore, $I([\mathrm{S}_l, \mathrm{S}_{i_1}, \mathrm{S}_{i_2}])$ is given by [29, eq. (19)]

$$\begin{aligned} &I([\mathrm{S}_l, \mathrm{S}_{i_1}, \mathrm{S}_{i_2}]) \\ &= \begin{cases} \log_2(1 + \gamma_{\mathrm{S}_l,\mathrm{S}_{i_2}}), & I([\mathrm{S}_l, \mathrm{S}_{i_1}]) < TR, \\ \log_2(1 + \gamma_{\mathrm{S}_l,\mathrm{S}_{i_2}} + \gamma_{\mathrm{S}_{i_1},\mathrm{S}_{i_2}}), & I([\mathrm{S}_l, \mathrm{S}_{i_1}]) \geq TR. \end{cases} \end{aligned} \tag{2}$$

where R denotes the end-to-end spectral efficiency in bps/Hz, and T denotes the total number of time slots for end-to-end transmission.[5] Generally, at the i_m-th relaying terminal S_{i_m} for $m = 1, \cdots, M-1$, the mutual information $I([\mathrm{S}_l, \mathrm{S}_{i_1}, \cdots, \mathrm{S}_{i_m}])$ is involved with m signal paths: a direct-path $\mathcal{L}(\mathrm{S}_l \rightarrow \mathrm{S}_{i_m})$ and $m-1$ relay-paths, i.e. $\mathcal{L}(\mathrm{S}_l \rightarrow \mathrm{S}_{i_1} \rightarrow \mathrm{S}_{i_m})$, $\mathcal{L}(\mathrm{S}_l \rightarrow \mathrm{S}_{i_1} \rightarrow \mathrm{S}_{i_2} \rightarrow \mathrm{S}_{i_m})$, $\cdots$, and $\mathcal{L}(\mathrm{S}_l \rightarrow \mathrm{S}_{i_1} \rightarrow \mathrm{S}_{i_2} \rightarrow \cdots \rightarrow \mathrm{S}_{i_{m-1}} \rightarrow \mathrm{S}_{i_m})$. Therefore, $I([\mathrm{S}_l, \mathrm{S}_{i_1}, \cdots, \mathrm{S}_{i_m}])$ is given by

$$I([\mathrm{S}_l, \mathrm{S}_{i_1}, \cdots, \mathrm{S}_{i_m}]) = \log_2\Big(1 + \gamma_{\mathrm{S}_l,\mathrm{S}_{i_m}} + \sum_{k=1}^{m-1} \delta_{i_k}\gamma_{\mathrm{S}_{i_k},\mathrm{S}_{i_m}}\Big), \tag{3}$$

where $m = 1, \cdots, M-1$. In the above equation, $\delta_{i_k} = 0$ if the mutual information $I([\mathrm{S}_l, \mathrm{S}_{i_1}, \cdots, \mathrm{S}_{i_k}])$ at S_{i_k} is smaller than TR, i.e. $I([\mathrm{S}_l, \mathrm{S}_{i_1}, \cdots, \mathrm{S}_{i_k}]) < TR$; $\delta_{i_k} = 1$ if $I([\mathrm{S}_l, \mathrm{S}_{i_1}, \cdots, \mathrm{S}_{i_k}])$ is greater than or equal to TR, i.e. $I([\mathrm{S}_l, \mathrm{S}_{i_1}, \cdots, \mathrm{S}_{i_k}]) \geq TR$.

Finally, we consider the mutual information at the relay R. The mutual information $I([\mathcal{C}_\mathrm{S}(l), \mathrm{R}])$ at R is involved with M signal paths: a direct-path $\mathcal{L}(\mathrm{S}_l \rightarrow \mathrm{R})$ and $M-1$ relay-paths, i.e. $\mathcal{L}(\mathrm{S}_l \rightarrow \mathrm{S}_{i_1} \rightarrow \mathrm{R})$, $\mathcal{L}(\mathrm{S}_l \rightarrow \mathrm{S}_{i_1} \rightarrow \mathrm{S}_{i_2} \rightarrow \mathrm{R})$, $\cdots$, and $\mathcal{L}(\mathrm{S}_l \rightarrow \mathrm{S}_{i_1} \rightarrow \mathrm{S}_{i_2} \rightarrow \cdots \rightarrow \mathrm{S}_{i_{M-1}} \rightarrow \mathrm{R})$. In a similar way to (3), $I([\mathcal{C}_\mathrm{S}(l), \mathrm{R}])$ is given by

$$I([\mathcal{C}_\mathrm{S}(l), \mathrm{R}]) = \log_2\Big(1 + \gamma_{\mathrm{S}_l,\mathrm{R}} + \sum_{m=1}^{M-1} \delta_{i_m}\gamma_{\mathrm{S}_{i_m},\mathrm{R}}\Big). \tag{4}$$

Remark 1: Since the mutual information expression of (4) is very general, it can be applied to any DF-based multi-hop cooperative diversity network. When only two sources cooperate in a network, i.e. $M = 2$, the mutual information $I([\mathcal{C}_\mathrm{S}(l), \mathrm{R}])$ of (4) reduces to the well-known result [29, eq. (19)]. Also, when there is no direct-path from S_l to R and no cooperation among $\{\mathrm{S}_{i_m}\}_{m=1}^{M-1}$, which is equivalent to the traditional two-hop relay network, the mutual information $I([\mathcal{C}_\mathrm{S}(l), \mathrm{R}])$ of (4) reduces to the well-known result [14, eq. (8)]:

$$I([\mathcal{C}_\mathrm{S}(l), \mathrm{R}]) = \log_2\Big(1 + \sum_{m=1}^{M-1} \bar{\delta}_{i_m}\gamma_{\mathrm{S}_{i_m},\mathrm{R}}\Big), \tag{5}$$

where $\bar{\delta}_{i_m} = 0$ if $I([\mathrm{S}_l, \mathrm{S}_{i_m}]) < 2R$; and $\bar{\delta}_{i_m} = 1$ if $I([\mathrm{S}_l, \mathrm{S}_{i_m}]) \geq 2R$.

C. Mutual Information for Second Hop

In this subsection, we investigate the mutual information in the second hop from the relay to L destinations. Similarly to the first hop, in the second hop, multiple destinations can cooperate with one another, which will be referred to as "destination-cooperation." As a special case, when $N = 1$, there exist only a direct transmission from the relay to the desired destination, which will be referred to as "no-destination-cooperation." Suppose N destinations out of L destinations are involved in the destination-cooperation, where $1 \leq N \leq L$. Without loss of generality, we assume D_l is the desired destination, and other $N-1$ destinations

[5]The exact value of T will be determined when the end-to-end transmission strategy is specified. Specifically, if M sources and N destinations are involved in cooperation, then the value T is given by $T = M + N$, which will be explained in Sections III and V.

relay the signal in the order $\mathrm{D}_{j_1}, \mathrm{D}_{j_2}, \cdots, \mathrm{D}_{j_{N-1}}$. This scenario can be represented by a row vector of N destinations $[\mathrm{D}_{j_1}, \mathrm{D}_{j_2}, \cdots, \mathrm{D}_{j_{N-1}}, \mathrm{D}_l] =: \mathcal{C}_\mathrm{D}(l)$. Taking a step similar to (4), $I([\mathrm{R}, \mathcal{C}_\mathrm{D}(l)])$ is given by

$$I([\mathrm{R}, \mathcal{C}_\mathrm{D}(l)]) = \log_2\left(1 + \gamma_{\mathrm{R},\mathrm{D}_l} + \sum_{n=1}^{N-1} \delta_{j_n} \gamma_{\mathrm{D}_{j_n},\mathrm{D}_l}\right). \quad (6)$$

In the above equation, $\delta_{j_n} = 0$ if the mutual information $I([\mathrm{R}, \mathrm{D}_{j_1}, \cdots, \mathrm{D}_{j_n}])$ at D_{j_n} is smaller than TR, i.e. $I([\mathrm{R}, \mathrm{D}_{j_1}, \cdots, \mathrm{D}_{j_n}]) < TR$; and $\delta_{j_n} = 1$ if $I([\mathrm{R}, \mathrm{D}_{j_1}, \cdots, \mathrm{D}_{j_n}])$ is greater than or equal to TR, i.e. $I([\mathrm{R}, \mathrm{D}_{j_1}, \cdots, \mathrm{D}_{j_n}]) \geq TR$.

III. End-to-End Transmission Strategies for Two Source-Destination Pairs

In this section, we first consider four *end-to-end* transmission strategies for two source-destination pairs, and then compare the four strategies.

A. Four End-to-End Transmission Strategies

There are many possible *end-to-end* transmission strategies depending on if cooperation is adopted or not in each hop. In this subsection, we classify the end-to-end transmission strategies into four possibilities: 1) a transmission strategy involving no-source-cooperation in the first hop and no-destination-cooperation in the second hop, which will be referred to as "no-cooperation-at-all"; 2) a transmission strategy involving source-cooperation in the first hop and no-destination-cooperation in the second hop, which will be referred to as "source-cooperation-only"; 3) a transmission strategy involving no-source-cooperation in the first hop and destination-cooperation in the second hop, which will be referred to as "destination-cooperation-only"; 4) a transmission strategy involving source-cooperation in the first hop and destination-cooperation in the second hop, which will be referred to as "source-destination-cooperation."

For the no-cooperation-at-all, there are two possibilities in source-destination pair selection: 1) S_1-D_1 pair is selected, which involves $\mathcal{L}(\mathrm{S}_1 \rightarrow \mathrm{R} \rightarrow \mathrm{D}_1)$; or 2) S_2-D_2 pair is selected, which involves $\mathcal{L}(\mathrm{S}_2 \rightarrow \mathrm{R} \rightarrow \mathrm{D}_2)$. Note that for each case, the signal transmitted from S_l involves two detections: one is at R, and the other is at D_l. Therefore, the mutual information $\mathcal{I}_{1,l}$ for the l-th case can be expressed by the minimum of $\mathcal{I}([\mathrm{S}_l, \mathrm{R}])$ and $\mathcal{I}([\mathrm{R}, \mathrm{D}_l])$ as follows:[6]

$$\mathcal{I}_{1,l} = \frac{1}{2} \min\left[\mathcal{I}([\mathrm{S}_l, \mathrm{R}]), \mathcal{I}([\mathrm{R}, \mathrm{D}_l])\right], \quad (7)$$

[6]The end-to-end mutual information in DF-based multi-hop systems is expressed by the minimum of the mutual information of each hop. For instance, in [30, eq. 8] and [31, eq. 11], the outage probabilities are formulated that way. Also, each destination must know the channel coefficients from its corresponding source to the relay as in numerous previous works on DF-based cooperative diversity networks [23]–[25]. In a small number of works on DF-based networks, however, a different channel assumption has been made. Specifically, in [26], [27], for a network with one source-destination pair and multiple relays, it was assumed that the destination knew *only* the channel coefficients from the relays to the destination. In this limited channel information case, however, it has been shown that the system did *not* achieve the full diversity order [26], and thus, the performance seriously deteriorates especially in the high SNR regime. Furthermore, taking steps similar to [28], the destinations can collect the channel coefficients.

for $l = 1, 2$. In the above equation, we use the constant $1/2$ because communication from S_l to D_l is done during two time slots.

For the source-cooperation-only, there are two possibilities: 1) S_1-D_1 pair is selected, which involves $\mathcal{L}(\mathrm{S}_1 \xrightarrow{\rightarrow \mathrm{S}_2 \rightarrow} \mathrm{R} \rightarrow \mathrm{D}_1)$; or 2) S_2-D_2 pair is selected, which involves $\mathcal{L}(\mathrm{S}_2 \xrightarrow{\rightarrow \mathrm{S}_1 \rightarrow} \mathrm{R} \rightarrow \mathrm{D}_2)$. Taking a step similar to (7), the mutual information $\mathcal{I}_{2,l}$ for the l-th case is given by

$$\mathcal{I}_{2,l} = \frac{1}{3} \min\left[\mathcal{I}([\mathrm{S}_l, \mathrm{S}_{3-l}, \mathrm{R}]), \mathcal{I}([\mathrm{R}, \mathrm{D}_l])\right], \quad (8)$$

for $l = 1, 2$. In the above equations, we use the constant $1/3$ because communication from S_l to D_l is done during three time slots.

For the destination-cooperation-only, there are two possibilities: 1) S_1-D_1 pair is selected, which involves $\mathcal{L}(\mathrm{S}_1 \rightarrow \mathrm{R} \xrightarrow{\rightarrow \mathrm{D}_2 \rightarrow} \mathrm{D}_1)$; or 2) S_2-D_2 pair is selected, which involves $\mathcal{L}(\mathrm{S}_2 \rightarrow \mathrm{R} \xrightarrow{\rightarrow \mathrm{D}_1 \rightarrow} \mathrm{D}_2)$. Taking a step similar to (7), the mutual information $\mathcal{I}_{3,l}$ for the l-th case is given by

$$\mathcal{I}_{3,l} = \frac{1}{3} \min\left[\mathcal{I}([\mathrm{S}_l, \mathrm{R}]), \mathcal{I}([\mathrm{R}, \mathrm{D}_{3-l}, \mathrm{D}_l])\right], \quad (9)$$

for $l = 1, 2$.

For the source-destination-cooperation, there are two possibilities: 1) S_1-D_1 pair is selected, which involves $\mathcal{L}(\mathrm{S}_1 \xrightarrow{\rightarrow \mathrm{S}_2 \rightarrow} \mathrm{R} \xrightarrow{\rightarrow \mathrm{D}_2 \rightarrow} \mathrm{D}_1)$; or 2) S_2-D_2 pair is selected, which involves $\mathcal{L}(\mathrm{S}_2 \xrightarrow{\rightarrow \mathrm{S}_1 \rightarrow} \mathrm{R} \xrightarrow{\rightarrow \mathrm{D}_1 \rightarrow} \mathrm{D}_2)$. Taking a step similar to (7), the mutual information $\mathcal{I}_{4,l}$ for the l-th case is given by

$$\mathcal{I}_{4,l} = \frac{1}{4} \min\left[\mathcal{I}([\mathrm{S}_l, \mathrm{S}_{3-l}, \mathrm{R}]), \mathcal{I}([\mathrm{R}, \mathrm{D}_{3-l}, \mathrm{D}_l])\right], \quad (10)$$

for $l = 1, 2$. In the above equations, we use the constant $1/4$ because communication from S_l to D_l is done during four time slots.

For each end-to-end transmission strategy, to maximize the mutual information, we select a single best source-destination pair out of two pairs in an opportunistic manner depending on channel conditions. This is an optimum source-destination pair selection problem for each of the four end-to-end transmission strategies. In order to maximize the mutual information, therefore, $\mathcal{I}_{1,l}$ of (7) or $\mathcal{I}_{2,l}$ of (8) or $\mathcal{I}_{3,l}$ of (9) or $\mathcal{I}_{4,l}$ of (10) must be maximized. This problem can be formulated as a max-min problem. Depending on channel conditions, the index $l_{\mathrm{opt},j}$ of a single best source-destination pair is determined by the max-min criterion as follows:[7]

$$l_{\mathrm{opt},j} = \arg\max_{l=1,2} \mathcal{I}_{j,l}, \quad (11)$$

where $j = 1, 2, 3, 4$. In Figs. 2, 3, and 4, the no-cooperation-at-all, source-cooperation-only, and source-destination-cooperation are depicted, respectively.

Remark 2: The four end-to-end transmission strategies can be considered as two individual traditional cooperative systems connected by the relay. However, there are some differences

[7]With this criterion, two sources might have different opportunity to transmit the signals. However, one can overcome this unfairness by adopting many techniques in multiuser systems such as the proportional fairness algorithm and/or adaptive modulation with different transmission power at the two sources [11], [12].

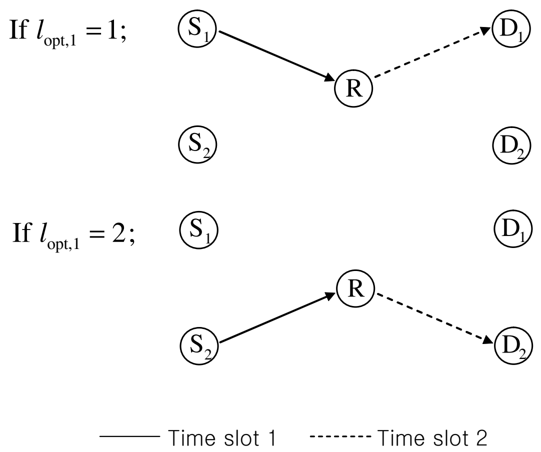


Fig. 2. The no-cooperation-at-all.

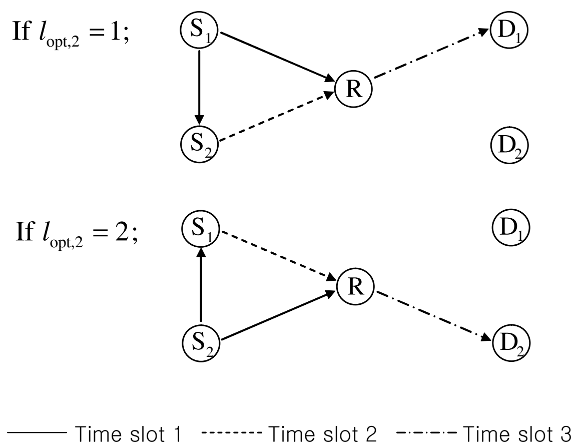


Fig. 3. The source-cooperation-only.

between the traditional cooperative diversity system and the way used in our paper. First, in traditional cooperative diversity systems, each terminal has its own unique role irrespective of channel conditions, whereas in our system, each terminal has different role depending on channel conditions in an opportunistic manner, i.e. sources/destinations can serves as relays. Secondly, we combine traditional cooperation with opportunistic transmission.

B. Comparison of Four End-To-End Transmission Strategies

In this subsection, we compare the four end-to-end transmission strategies: no-cooperation-at-all, source-cooperation-only, destination-cooperation-only, and source-destination-cooperation in terms of outage performance.[8] Note that the four end-to-end strategies require different time slots and different total transmission power: the no-cooperation-at-all needs two time slots ($T = 2$) and consumes $2\mathcal{P}$; both the source-cooperation-only and destination-cooperation-only need three time slots ($T = 3$) and consume $3\mathcal{P}$; and the

[8]For coded systems, there are two important performance measures in the literature: ergodic capacity and outage capacity (outage performance). Although ergodic capacity is theoretically an important performance measure, it may be considered as rather unsuitable in practical systems [32]. On the other hand, outage capacity is actually considered as more suitable in practice [32]. As in many previous works [13], [14], [30], therefore, we adopt outage performance as a performance measure and the mutual information as a selection criterion.

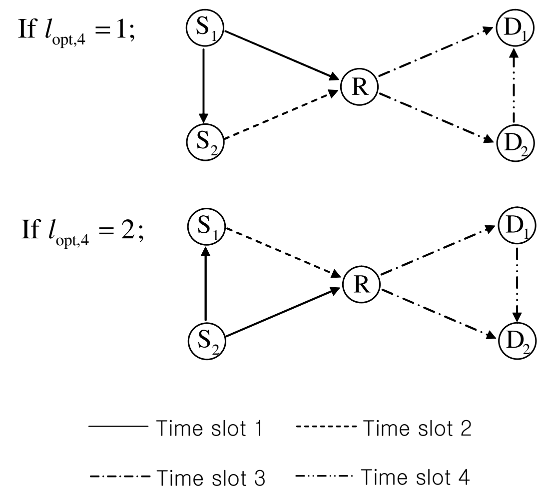


Fig. 4. The source-destination-cooperation.

source-destination-cooperation needs four time slots ($T = 4$) and consumes $4\mathcal{P}$. For a fair comparison of the four transmission strategies, we must make the total transmission power the same. To this end, we introduce a power scale factor κ as follows: $\kappa = 1$ for the no-cooperation-at-all; $\kappa = 2/3$ for both the source-cooperation-only and destination-cooperation-only; and $\kappa = 1/2$ for the source-destination-cooperation. Then we use $\kappa\gamma$ instead of γ in (4) and (6), where $\gamma \in \{\gamma_{S_1,S_2}, \gamma_{D_1,D_2}, \gamma_{S_l,R}, \gamma_{R,D_l} : l = 1,2\}$. As a result, the total transmission power of all the four end-to-end transmission strategies becomes identical, and it is $2\mathcal{P}$.

Then we investigate the outage performance of the four end-to-end transmission strategies. We let $P_{out,1}$, $P_{out,2}$, $P_{out,3}$, and $P_{out,4}$ denote the outage probabilities of the no-cooperation-at-all, source-cooperation-only, destination-cooperation-only, and source-destination-cooperation, respectively, where $P_{out,j}$ is given by $P_{out,j} = \Pr\big[\max_{l=1,2} \mathcal{I}_{j,l} < R\big]$ for $j = 1,2,3,4$. In Section VI, the four outage probabilities will be numerically compared. Interestingly, it will turn out that a particular strategy is *not always* better than another strategy. That is, depending on channel conditions, the four end-to-end transmission strategies complement one another in terms of outage performance. This observation motivates us to propose an optimum selection of one strategy out of the four possible end-to-end transmission strategies, along with an optimum source-destination pair.

Remark 3: We could analytically derive the exact outage probabilities $\{P_{out,j} : j = 1,2,3,4\}$ in closed-form. Specifically, taking a step similar to [14, eq. (20)], it is easy to derive $P_{out,1}$. Also, taking steps similar to those used in Appendices A and B, it is possible to derive $\{P_{out,j} : j = 2,3,4\}$. The final expressions, however, are not presented in this paper because they are too long to be presented due to the page limit. Furthermore, our final objective is not to propose or use *individually* the four end-to-end transmission strategies. Instead, we will propose a jointly (or globally) optimum scheme, and its exact outage probability in closed-form will be presented in the next section.

IV. Optimum Joint Selection Scheme for Two Source-Destination Pairs

In this section, we first propose an optimum joint scheme for source-destination pair selection and transmission strategy selection. That is, we jointly select a single best source-destination pair and a single best end-to-end transmission strategy. Then we show that the optimum joint selection scheme can be simplified without loss of outage performance. Finally, we derive the exact outage probability.

A. Joint Source-Destination Pair Selection and Transmission Strategy Selection

In this subsection, we consider *joint optimum selection* for both a best source-destination pair out of two source-destination pairs and a best transmission strategy out of the four end-to-end transmission strategies. This will be referred to as the "joint selection (JS)." In this paper, the joint selection is made such that the mutual information is maximized. That is, the index $j_{\rm JS}$ of the selected end-to-end transmission strategy and the index $l_{\rm JS}$ of the selected source-destination pair are jointly determined as follows:

$$(j_{\rm JS}, l_{\rm JS}) = \arg \max_{\substack{j=1,2,3,4 \\ l=1,2}} \mathcal{I}_{j,l}. \tag{12}$$

The mutual information $\mathcal{I}_{\rm JS}$ for the joint selection can be expressed by the maximum of $\{\mathcal{I}_{j,l},:\ j = 1,2,3,4, l = 1,2\}$ as follows: $\mathcal{I}_{\rm JS} = \max_{\substack{j=1,2,3,4 \\ l=1,2}} \mathcal{I}_{j,l} = \mathcal{I}_{j_{\rm JS},l_{\rm JS}}$. Then, using (7), (8), (9), and (10), the outage probability $P_{\rm out}^{\rm JS}(R; \bar{\gamma}_{\rm S_1,R}, \bar{\gamma}_{\rm S_2,R}, \bar{\gamma}_{\rm R,D_1}, \bar{\gamma}_{\rm R,D_2}, \bar{\gamma}_{\rm S_1,S_1}, \bar{\gamma}_{\rm D_1,D_2})$ of the joint selection is given by

$$\begin{aligned} &P_{\rm out}^{\rm JS}(R; \bar{\gamma}_{\rm S_1,R}, \bar{\gamma}_{\rm S_2,R}, \bar{\gamma}_{\rm R,D_1}, \bar{\gamma}_{\rm R,D_2}, \bar{\gamma}_{\rm S_1,S_1}, \bar{\gamma}_{\rm D_1,D_2}) \\ &= \Pr[\mathcal{I}_{\rm JS} < R] \\ &= \Pr\left[\mathcal{I}_{1,l_{\rm opt,1}} < R, \mathcal{I}_{2,l_{\rm opt,2}} < R, \mathcal{I}_{3,l_{\rm opt,3}} < R, \mathcal{I}_{4,l_{\rm opt,4}} < R\right]. \end{aligned} \tag{13}$$

It is *possible* to derive the exact outage probability of the joint selection by directly solving (13). However, since $\{\mathcal{I}_{j,l} : j = 1,2,3,4, l = 1,2\}$ are correlated one another, it is very lengthy and complicated to directly solve (13). Therefore, we take another approach, which is simpler, more useful, and more insightful. Specifically, we first consider another but simpler joint selection method, and then we prove that this simpler joint selection method is equivalent to the original joint selection in terms of outage performance. Finally, by deriving the outage probability of the simpler joint selection method, we obtain the outage probability of the original joint selection.

Remark 4: Our system is quite similar to a system in interference channel, where two sources transmit the signals at the same time [33]–[35]. However, there are still many different aspects between our work and the interference channel. In fact, there are tradeoffs between two systems: our system is more reliable, whereas a system in interference channel is more bandwidth efficient.

B. Simplified Joint Selection

In this subsection, we consider another but simpler joint selection method, which involves only three end-to-end transmission strategies: no-cooperation-at-all, source-cooperation-only, and destination-cooperation-only. This will be referred to as "simplified joint selection (SJS)" in this paper. Taking a step similar to (12), the index $j_{\rm SJS}$ of the selected end-to-end transmission strategy and the index $l_{\rm SJS}$ of the selected source-destination pair are jointly determined as follows:

$$(j_{\rm SJS}, l_{\rm SJS}) = \arg \max_{\substack{j=1,2,3 \\ l=1,2}} \mathcal{I}_{j,l}. \tag{14}$$

Also, the mutual information $\mathcal{I}_{\rm SJS}$ for the simplified joint selection can be expressed by the maximum of $\{\mathcal{I}_{j,l},:\ j = 1,2,3, l = 1,2\}$ as follows: $\mathcal{I}_{\rm SJS} = \max_{\substack{j=1,2,3 \\ l=1,2}} \mathcal{I}_{j,l} = \mathcal{I}_{j_{\rm SJS},l_{\rm SJS}}$. Note that $\mathcal{I}_{\rm SJS}$ involves only $\{\mathcal{I}_{j,l},:\ j = 1,2,3, l = 1,2\}$ without $\{\mathcal{I}_{4,l},:\ l = 1,2\}$. Then, using (7), (8), and (9), the outage probability $P_{\rm out}^{\rm JS}(R; \bar{\gamma}_{\rm S_1,R}, \bar{\gamma}_{\rm S_2,R}, \bar{\gamma}_{\rm R,D_1}, \bar{\gamma}_{\rm R,D_2}, \bar{\gamma}_{\rm S_1,S_1}, \bar{\gamma}_{\rm D_1,D_2})$ of the simplified joint selection is given by

$$\begin{aligned} &P_{\rm out}^{\rm SJS}(R; \bar{\gamma}_{\rm S_1,R}, \bar{\gamma}_{\rm S_2,R}, \bar{\gamma}_{\rm R,D_1}, \bar{\gamma}_{\rm R,D_2}, \bar{\gamma}_{\rm S_1,S_1}, \bar{\gamma}_{\rm D_1,D_2}) \\ &= \Pr[\mathcal{I}_{\rm SJS} < R] \\ &= \Pr\left[\mathcal{I}_{1,l_{\rm opt,1}} < R, \mathcal{I}_{2,l_{\rm opt,2}} < R, \mathcal{I}_{3,l_{\rm opt,3}} < R\right]. \end{aligned} \tag{15}$$

C. Outage Probability

In this subsection, we first show the simplified joint selection is equivalent to the original joint selection in terms of outage performance.

Theorem 1: The outage probability of the simplified joint selection is identical to the outage probability of the joint selection, i.e. $P_{\rm out}^{\rm SJS}(R; \bar{\gamma}_{\rm S_1,R}, \bar{\gamma}_{\rm S_2,R}, \bar{\gamma}_{\rm R,D_1}, \bar{\gamma}_{\rm R,D_2}, \bar{\gamma}_{\rm S_1,S_1}, \bar{\gamma}_{\rm D_1,D_2}) = P_{\rm out}^{\rm JS}(R; \bar{\gamma}_{\rm S_1,R}, \bar{\gamma}_{\rm S_2,R}, \bar{\gamma}_{\rm R,D_1}, \bar{\gamma}_{\rm R,D_2}, \bar{\gamma}_{\rm S_1,S_1}, \bar{\gamma}_{\rm D_1,D_2})$.

Proof: See Appendix A. □

In Section VI, this theorem will be confirmed numerically. In fact, one could intuitively expect the result of Theorem 1 as follows. First, one can determine the outage status of the no-cooperation-at-all, joint selection, and simplified joint selection depending on $(\gamma_{\rm S_1,R}, \gamma_{\rm S_2,R}, \gamma_{\rm R,D_1}, \gamma_{\rm R,D_2})$, which is tabulated in Table I. As can be seen in the table, only for two cases, $Case$ 4 and $Case$ 7, the original joint selection has different outage status from the no-cooperation-at-all. Since the combination of the source-cooperation-only and destination-cooperation-only can cover the two cases, the source-destination-cooperation does not need to be actually involved. That is, outage performance of the joint selection does not deteriorate even if the source-destination-cooperation is not involved. Therefore, the joint selection is equivalent to the simplified joint selection in terms of outage performance.[9]

From Theorem 1, we can derive some interesting and important implications as follows. Firstly, adding the possibility of the source-destination-cooperation does not actually improve the outage performance. Therefore, in the implementation of a practical system, one just needs to combine the three

[9]Therefore, the mutual information $\mathcal{I}_{\rm JS}$ of the joint selection and that $\mathcal{I}_{\rm SJS}$ of the simplified joint selection are equivalent in the sense of "equal in distribution" [36].

TABLE I
OUTAGE STATUS OF THE NO-COOPERATION-AT-ALL, JOINT SELECTION, AND SIMPLIFIED JOINT SELECTION DEPENDING ON $(\gamma_{S_1,R}, \gamma_{S_2,R}, \gamma_{R,D_1}, \gamma_{R,D_2})$. ○: ALWAYS IN OUTAGE; ×: NOT IN OUTAGE; △: MAY NOT IN OUTAGE. $R_1 = 2^{2R} - 1$.

$\gamma_{S_1,R}$	$\gamma_{S_2,R}$	γ_{R,D_1}	γ_{R,D_2}	No-cooperation-at-all	Joint selection	Simplified joint selection	
$< R_1$	$< R_1$	$< R_1$	$< R_1$	○	○	○	*Case* 1
$< R_1$	$\geq R_1$	$< R_1$	$< R_1$	○	○	○	
$\geq R_1$	$< R_1$	$< R_1$	$< R_1$	○	○	○	
$\geq R_1$	$\geq R_1$	$< R_1$	$< R_1$	○	○	○	
$< R_1$	$< R_1$	$< R_1$	$\geq R_1$	○	○	○	*Case* 2
$< R_1$	$\geq R_1$	$< R_1$	$\geq R_1$	×	×	×	*Case* 3
$\geq R_1$	$< R_1$	$< R_1$	$\geq R_1$	○	△	△	*Case* 4
$\geq R_1$	$\geq R_1$	$< R_1$	$\geq R_1$	×	×	×	*Case* 5
$< R_1$	$< R_1$	$\geq R_1$	$< R_1$	○	○	○	*Case* 6
$< R_1$	$\geq R_1$	$\geq R_1$	$< R_1$	○	△	△	*Case* 7
$\geq R_1$	$< R_1$	$\geq R_1$	$< R_1$	×	×	×	*Case* 8
$\geq R_1$	$\geq R_1$	$\geq R_1$	$< R_1$	×	×	×	
$< R_1$	$< R_1$	$\geq R_1$	$\geq R_1$	○	○	○	*Case* 9
$< R_1$	$\geq R_1$	$\geq R_1$	$\geq R_1$	×	×	×	*Case* 10
$\geq R_1$	$< R_1$	$\geq R_1$	$\geq R_1$	×	×	×	
$\geq R_1$	$\geq R_1$	$\geq R_1$	$\geq R_1$	×	×	×	

possible end-to-end transmission strategies, not the whole four transmission strategies. This makes the system implementation easier and simpler. Secondly, this simplification makes grouping easy when multiple source-destination pairs exist. Since the number of possible strategies increases exponentially as the cardinality of a group increases, one should restrict the number of source-destination pairs in a group to be one or two in practice. In grouping, it is not always possible to find two source-destination pairs such that both two sources are relatively closer each other and two destinations are relatively closer each other at the same time. If we utilize Theorem 1, one can partition a group, where two sources are relatively closer each other or two destinations are relatively closer each other, which will be explained in Section V.B. Thirdly, in order to derive the outage probability of (13), one can tackle a simpler problem of (15), not the original problem of (13). This makes the outage performance analysis much simpler. In the following theorem, we derive the outage probability of the simplified joint selection.

Theorem 2: The *exact closed-form* outage probability $P_{\text{out}}^{\text{SJS}}(R; \bar{\gamma}_{S_1,R}, \bar{\gamma}_{S_2,R}, \bar{\gamma}_{R,D_1}, \bar{\gamma}_{R,D_2}, \bar{\gamma}_{S_1,S_1}, \bar{\gamma}_{D_1,D_2})$ of the simplified joint selection is given by

$$\begin{aligned} &P_{\text{out}}^{\text{SJS}}(R; \bar{\gamma}_{S_1,R}, \bar{\gamma}_{S_2,R}, \bar{\gamma}_{R,D_1}, \bar{\gamma}_{R,D_2}, \bar{\gamma}_{S_1,S_1}, \bar{\gamma}_{D_1,D_2}) \\ &\quad = \sum_{i=1}^{4} \Psi_i + \Psi_5(\bar{\gamma}_{S_1,R}, \bar{\gamma}_{S_2,R}, \bar{\gamma}_{R,D_1}, \bar{\gamma}_{R,D_2}) \\ &\qquad + \Psi_5(\bar{\gamma}_{S_2,R}, \bar{\gamma}_{S_1,R}, \bar{\gamma}_{R,D_2}, \bar{\gamma}_{R,D_1}), \end{aligned} \tag{16}$$

where

$$\Psi_1 = \Xi_0(R_1; \bar{\gamma}_{R,D_1})\Xi_0(R_1; \bar{\gamma}_{R,D_2}), \tag{17}$$

$$\begin{aligned}\Psi_2 &= \Xi_0(R_1; \bar{\gamma}_{S_1,R})\Xi_0(R_1; \bar{\gamma}_{S_2,R}) \\ &\quad \times \Xi_0(R_1; \bar{\gamma}_{R,D_1})\Xi_1(R_1; \bar{\gamma}_{R,D_2}),\end{aligned} \tag{18}$$

$$\begin{aligned}\Psi_3 &= \Xi_0(R_1; \bar{\gamma}_{S_1,R})\Xi_0(R_1; \bar{\gamma}_{S_2,R}) \\ &\quad \times \Xi_1(R_1; \bar{\gamma}_{R,D_1})\Xi_0(R_1; \bar{\gamma}_{R,D_2}),\end{aligned} \tag{19}$$

$$\begin{aligned}\Psi_4 &= \Xi_0(R_1; \bar{\gamma}_{S_1,R})\Xi_0(R_1; \bar{\gamma}_{S_2,R}) \\ &\quad \times \Xi_1(R_1; \bar{\gamma}_{R,D_1})\Xi_1(R_1; \bar{\gamma}_{R,D_2}),\end{aligned} \tag{20}$$

$$\begin{aligned} &\Psi_5(\bar{\gamma}_1, \bar{\gamma}_2, \bar{\gamma}_3, \bar{\gamma}_4) \\ &= \Xi_1(R_1; \bar{\gamma}_1)\Xi_0(R_1; \bar{\gamma}_2)\Xi_0(R_1; \bar{\gamma}_3)\Xi_2(R_2, R_1; \bar{\gamma}_4) \\ &\quad + \Xi_0(R_1; \bar{\gamma}_3)\Xi_1(R_2; \bar{\gamma}_4)\Xi_1(R_2; \bar{\gamma}_{S_1,S_2})\Xi_5(R_2, R_1; \bar{\gamma}_1, \bar{\gamma}_2) \\ &\quad + \Xi_0(R_1; \bar{\gamma}_2)\Xi_1(R_2; \bar{\gamma}_3)\Xi_0(R_2; \bar{\gamma}_{S_1,S_2}) \\ &\quad \times \Xi_3(R_2, R_1; \bar{\gamma}_1, \bar{\gamma}_3, \bar{\gamma}_{D_1,D_2}), \end{aligned} \tag{21}$$

with $R_1 = 2^{2R} - 1$ and $R_2 = \frac{3}{2}(2^{3R} - 1)$. In the above equations,

$$\Xi_0(R_0; \bar{\gamma}) = 1 - \exp(-R_0/\bar{\gamma}), \tag{22}$$

$$\Xi_1(R_0; \bar{\gamma}) = \exp(-R_0/\bar{\gamma}), \tag{23}$$

$$\Xi_2(R_2, R_1; \bar{\gamma}) = \Xi_0(R_2; \bar{\gamma}) - \Xi_0(R_1; \bar{\gamma}), \tag{24}$$

$$\begin{aligned}\Xi_3(R_2, R_1; \xi_1, \xi_2, \xi_3) &= \Xi_2(R_2, R_1; \xi_1) + \Xi_4(R_2, R_1; \xi_2, \xi_3) \\ &\quad - \Xi_2(R_2, R_1; \xi_1)\Xi_4(R_2, R_1; \xi_2, \xi_3),\end{aligned} \tag{25}$$

$$\begin{aligned} &\Xi_4(R_2, R_1; \xi_1, \xi_2) \\ &= \begin{cases} \Xi_0(R_1; \xi_1) \\ -\frac{\xi_2}{\xi_2 - \xi_1}\Xi_1(R_2; \xi_2)\Xi_0\left(R_1; \frac{\xi_1\xi_2}{\xi_2 - \xi_1}\right), & \xi_1 \neq \xi_2, \\ \Xi_0(R_1; \xi_1) - \frac{R_1}{\xi_1}\Xi_1(R_2; \xi_1), & \xi_1 = \xi_2, \end{cases} \end{aligned} \tag{26}$$

$$\begin{aligned} &\Xi_5(R_2, R_1; \xi_1, \xi_2) \\ &= \begin{cases} \Xi_0(R_1; \xi_1)\Xi_1(R_1; \xi_2) \\ -\frac{\xi_2}{\xi_2 - \xi_1}\Xi_1(R_2; \xi_2)\Xi_0\left(R_1; \frac{\xi_1\xi_2}{\xi_2 - \xi_1}\right), & \xi_1 \neq \xi_2, \\ \Xi_0(R_1; \xi_1)\Xi_1(R_1; \xi_1) - \frac{R_1}{\xi_1}\Xi_1(R_2; \xi_1), & \xi_1 = \xi_2. \end{cases} \end{aligned} \tag{27}$$

Proof: See Appendix B. □

Note that by Theorem 1, the exact closed-form outage probability $P_{\text{out}}^{\text{JS}}(R; \bar{\gamma}_{S_1,R}, \bar{\gamma}_{S_2,R}, \bar{\gamma}_{R,D_1}, \bar{\gamma}_{R,D_2}, \bar{\gamma}_{S_1,S_1}, \bar{\gamma}_{D_1,D_2})$ of the original joint selection is given by (16) as well. In the following, we present diversity order of the simplified joint selection.

Lemma 1: The simplified joint selection achieves the full diversity order two.

Proof: When $\mathcal{P}$ goes to infinity, we have

$$\lim_{\mathcal{P}\to\infty} P_{\text{out}}^{\text{SJS}}(R;\bar{\gamma}_{\text{S}_1,\text{R}},\bar{\gamma}_{\text{S}_2,\text{R}},\bar{\gamma}_{\text{R},\text{D}_1},\bar{\gamma}_{\text{R},\text{D}_2},\bar{\gamma}_{\text{S}_1,\text{S}_1},\bar{\gamma}_{\text{D}_1,\text{D}_2}) = \frac{C_1}{\mathcal{P}^2} + \mathcal{O}\left(\frac{1}{\mathcal{P}^3}\right), \quad (28)$$

where C_1 is a constant. That is, $P_{\text{out}}^{\text{SJS}}(R;\bar{\gamma}_{\text{S}_1,\text{R}},\bar{\gamma}_{\text{S}_2,\text{R}},\bar{\gamma}_{\text{R},\text{D}_1},\bar{\gamma}_{\text{R},\text{D}_2},\bar{\gamma}_{\text{S}_1,\text{S}_1},\bar{\gamma}_{\text{D}_1,\text{D}_2})$ behaves like $1/\mathcal{P}^2$ as $\mathcal{P}$ approaches infinity. Thus, the diversity order of the simplified joint selection is two. □

Note that by Theorem 1, the the original joint selection also achieves the full diversity order two as well.

V. Multiple Source-Destination Pairs

In this section, we generalize the proposed transmission strategy into a network with L source-destination pairs. Specifically, we first propose an optimum end-to-end transmission strategy, and then a suboptimum end-to-end transmission strategy in order to reduce the signaling overhead and computational complexity. Finally, we derive the outage probability and diversity order of the suboptimum strategy.

A. Optimum End-to-End Transmission Strategy

In this subsection, we propose an optimum end-to-end transmission strategy for L source-destination pairs. Taking a step similar to (7) with $I([\mathcal{C}_\text{S}(l),\text{R}])$ of (4) and $I([\text{R},\mathcal{C}_\text{D}(l)])$ of (6), the end-to-end mutual information $I([\mathcal{C}_\text{S}(l),\text{R},\mathcal{C}_\text{D}(l)])$ is given by

$$I([\mathcal{C}_\text{S}(l),\text{R},\mathcal{C}_\text{D}(l)]) = \frac{1}{M+N}\min\left[I([\mathcal{C}_\text{S}(l),\text{R}]), I([\text{R},\mathcal{C}_\text{D}(l)])\right], \quad (29)$$

where we use the constant $1/(M+N)$ because communication from S_l to D_l is done during $M+N$ time slots. Depending on how many sources and destinations are involved in the source/destination-cooperation and on the ordering of the involved sources and destinations, there are $L\left(\sum_{k=0}^{L-1}\binom{L-1}{k}k!\right)^2$ end-to-end transmission strategies. Note that each end-to-end transmission strategy can have different performance in general. For a fair comparison of transmission power for all the end-to-end transmission strategies, as in Section III.B, we use $\bar{\kappa}\gamma$ instead of γ in (4) and (6), where $\gamma \in \{\gamma_{\text{S}_l,\text{S}_k},\gamma_{\text{D}_l,\text{D}_k},\gamma_{\text{S}_l,\text{R}},\gamma_{\text{R},\text{D}_l} : l,k = 1,\cdots,L \text{ and } k\neq l\}$ and $\bar{\kappa} = \rho/(M+N)$ with a positive real value ρ. As a result, the total transmission power of all the end-to-end transmission strategies becomes identical, and it is $\rho\mathcal{P}$.

In order to maximize the mutual information $I([\mathcal{C}_\text{S}(l),\text{R},\mathcal{C}_\text{D}(l)])$ of (29), the index of selected source-destination pair $\hat{l}$, the set of selected sources $\hat{\mathcal{C}}_\text{S}(\hat{l})$, and the set of selected destinations $\hat{\mathcal{C}}_\text{D}(\hat{l})$ are determined by the max-min criterion as follows:

$$(\hat{l},\hat{\mathcal{C}}_\text{S}(\hat{l}),\hat{\mathcal{C}}_\text{D}(\hat{l})) = \arg\max_{\substack{l=1,\cdots,L\\ \mathcal{C}_\text{S}(l)\in\mathcal{Q}_1(l)\\ \mathcal{C}_\text{D}(l)\in\mathcal{Q}_2(l)}} I([\mathcal{C}_\text{S}(l),\text{R},\mathcal{C}_\text{D}(l)]). \quad (30)$$

In the above equation, $\mathcal{Q}_1(l)$ denotes a set of vectors, which are made by enumerating all the possible orderings of any combination of $\{\text{S}_k : k = 1,\cdots,L, k\neq l\}$ when the transmitting source is S_l, i.e. $\mathcal{Q}_1(l) = \{[\text{S}_l],[\text{S}_l,\text{S}_1],\cdots,[\text{S}_l,\text{S}_L],[\text{S}_l,\text{S}_1,\text{S}_2],\cdots,[\text{S}_l,\text{S}_L,\text{S}_{L-1}],\cdots,[\text{S}_l,\text{S}_1,\text{S}_2,\cdots,\text{S}_{l-1},\text{S}_{l+1},\cdots,\text{S}_L],\cdots,[\text{S}_l,\text{S}_L,\text{S}_{L-1},\cdots,\text{S}_{l+1},\text{S}_{l-1},\cdots,\text{S}_1]\}$; $\mathcal{Q}_2(l)$ denotes a set of vectors, which are made by enumerating all the possible orderings of any combination of $\{\text{D}_k : k = 1,\cdots,L, k\neq l\}$ when the desired destination is D_l, i.e. $\mathcal{Q}_2(l) = \{[\text{D}_l],[\text{D}_1,\text{D}_l],\cdots,[\text{D}_L,\text{D}_l],[\text{D}_1,\text{D}_2,\text{D}_l],\cdots,[\text{D}_L,\text{D}_{L-1},\text{D}_l],\cdots,[\text{D}_1,\text{D}_2,\cdots,\text{D}_{l-1},\text{D}_{l+1},\cdots,\text{D}_L,\text{D}_l],\cdots,[\text{D}_L,\text{D}_{L-1},\cdots,\text{D}_{l+1},\text{D}_{l-1},\cdots,\text{D}_1,\text{D}_l]\}$.[10]

Note that the proposed optimum end-to-end transmission strategy of (30) maximizes the mutual information. However, there are two issues, which make the implementation difficult in practice. Firstly, in the optimum strategy, a controlling node determining the optimum transmission strategy must know all the channel coefficients in the entire network, which induces extremely high signaling overhead. Specifically, for L source-destination pairs, the controlling node must collect L^2+L channel coefficients, i.e. $\{h_{\text{S}_l,\text{R}},h_{\text{R},\text{D}_l},h_{\text{S}_l,\text{S}_k},h_{\text{D}_l,\text{D}_k} : l,k = 1\cdots,L,k\neq l\}$. Secondly, the controlling node must calculate all the end-to-end mutual information possibilities $\{I([\mathcal{C}_\text{S}(l),\text{R},\mathcal{C}_\text{D}(l)]) : l = 1,\cdots,L,\mathcal{C}_\text{S}(l)\in\mathcal{Q}_1(l),\mathcal{C}_\text{D}(l)\in\mathcal{Q}_2(l)\}$, which induces extremely high computational complexity. Specifically, for L source-destination pairs, an optimum strategy must be determined from $L\left(\sum_{k=0}^{L-1}\binom{L-1}{k}k!\right)^2$ possibilities. For example, there are 8 possibilities when $L=2$; 75 possibilities when $L=3$; and 1024 possibilities when $L=4$. In total, due to the high signaling overhead as well as high computational complexity, it is extremely difficult to implement the optimum strategy as is in practical systems. In order to reduce the signaling overhead as well as computational complexity, therefore, we will consider a suboptimum end-to-end transmission strategy in the next subsection.

B. Group-Based Suboptimum End-to-End Transmission Strategy

In this subsection, we propose a suboptimum end-to-end transmission strategy. For a sensor network which is one of major applications of cooperative diversity networks, there have been numerous approaches to reduce the signaling overhead and computational complexity. Among the approaches, a group-based partition method has been shown to be very effective in practical systems. In this paper, therefore, we adopt the group-based partition method, which divides a network into disjoint groups. Since the number of possible strategies increases exponentially as the cardinality of a group increases, we restrict the number of source-destination pairs in a group to be one or two. The proposed suboptimum strategy can be summarized as follows:

Group-Based Suboptimum Strategy:

1) Depending on distances (including the effect of the channel statistics) among terminals, L source-destination pairs are divided into disjoint groups, where each group has one/two source-destination pair(s). Specifically, we partition L source-destination pairs into disjoint groups such that either two sources *or* two

[10]The cardinality of $\mathcal{Q}_1(l)$ and that of $Q_2(l)$ are identical, i.e. $|\mathcal{Q}_1(l)| = |\mathcal{Q}_2(l)|$, and it is given by $\sum_{i=0}^{L-1}\binom{L-1}{i}i!$.

destinations within a single group are relatively closer to each other than to any other terminals not in the group. Note that in a group, it is *not* necessarily required that two sources are relatively closer each other *and* two destinations are relatively closer each other at the same time. That is, in a group, it is necessary that two sources are relatively closer each other or two destinations are relatively closer each other. This is because the source-cooperation and destination-cooperation do not actually need to be utilized simultaneously. Instead, either the source-cooperation or the destination-cooperation needs to be utilized as implied by Theorem 1, which shows that the joint selection (involving the source-destination-cooperation) and the simplified joint selection (not involving the source-destination-cooperation) are equivalent in terms of outage performance. That is, the source-destination-cooperation does not need to be actually involved in the joint selection.

2) Each group collects local channel coefficients and calculates its mutual information of the end-to-end transmission strategy. Let $\mathrm{S}_1^{(k)}, \mathrm{S}_2^{(k)}, \mathrm{D}_1^{(k)}$, and $\mathrm{D}_2^{(k)}$ be the first source, second source, first destination, and second destination in the k-th group $\mathcal{G}_k$, respectively, where $k = 1, \cdots, \mathcal{K}$ with the total number of groups $\mathcal{K}$. Note that the sum of cardinality of all the groups is $2L$, i.e. $\sum_{k=1}^{\mathcal{K}} |\mathcal{G}_k| = 2L$. Taking a step similar to (29), the mutual information $I([\mathcal{C}_\mathrm{S}^{(k)}(l_k), \mathrm{R}, \mathcal{C}_\mathrm{D}^{(k)}(l_k)])$ for $\mathcal{G}_k$ is given by

$$\begin{aligned} &I([\mathcal{C}_\mathrm{S}^{(k)}(l_k), \mathrm{R}, \mathcal{C}_\mathrm{D}^{(k)}(l_k)]) \\ &= \frac{1}{\bar{M}+\bar{N}} \min\left[I([\mathcal{C}_\mathrm{S}^{(k)}(l_k); \mathrm{R}]), I([\mathrm{R}; \mathcal{C}_\mathrm{D}^{(k)}(l_k)])\right]. \end{aligned} \tag{31}$$

In the above equation, $\mathcal{C}_\mathrm{S}^{(k)}(l_k) \in \left\{[\mathrm{S}_{l_k}^{(k)}], [\mathrm{S}_{l_k}^{(k)}, \mathrm{S}_{3-l_k}^{(k)}]\right\} =: \mathcal{Q}_1^{(k)}(l_k)$ and $|\mathcal{C}_\mathrm{S}^{(k)}(l_k)| = \bar{M}$; and $\mathcal{C}_\mathrm{D}^{(k)}(l_k) \in \left\{[\mathrm{D}_{l_k}^{(k)}], [\mathrm{D}_{3-l_k}^{(k)}, \mathrm{D}_{l_k}^{(k)}]\right\} =: \mathcal{Q}_1^{(k)}(l_k)$ and $|\mathcal{C}_\mathrm{D}^{(k)}(l_k)| = \bar{N}$, where $l_k = 1, 2$. If $\mathcal{G}_k$ has only one source-destination pair, i.e. $|\mathcal{G}_k| = 2$, then $\mathcal{C}_\mathrm{S}^{(k)}(l_k) = [\mathrm{S}_1^{(k)}]$ and $\mathcal{C}_\mathrm{D}^{(k)}(l_k) = [\mathrm{D}_1^{(k)}]$. Therefore, $I([\mathcal{C}_\mathrm{S}^{(k)}(l_k), \mathrm{R}, \mathcal{C}_\mathrm{D}^{(k)}(l_k)])$ of (31) reduces to

$$\begin{aligned} &I([\mathcal{C}_\mathrm{S}^{(k)}(l_k), \mathrm{R}, \mathcal{C}_\mathrm{D}^{(k)}(l_k)]) \\ &= \frac{1}{2} \min\left[I([\mathrm{S}_1^{(k)}, \mathrm{R}]), I([\mathrm{R}, \mathrm{D}_1^{(k)}])\right]. \end{aligned} \tag{32}$$

Taking a step similar to (30), the selected index $\hat{l}_k$ and the sets $\hat{\mathcal{C}}_\mathrm{S}^{(k)}(\hat{l}_k)$ and $\hat{\mathcal{C}}_\mathrm{D}^{(k)}(\hat{l}_k)$ are determined as follows:

$$\begin{aligned} &(\hat{l}_k, \hat{\mathcal{C}}_\mathrm{S}^{(k)}(\hat{l}_k), \hat{\mathcal{C}}_\mathrm{D}^{(k)}(\hat{l}_k)) \\ &= \arg \max_{\substack{l_k=1,2 \\ \mathcal{C}_\mathrm{S}^{(k)}(l_k) \in \mathcal{Q}_1^{(k)}(l_k) \\ \mathcal{C}_\mathrm{D}^{(k)}(l_k) \in \mathcal{Q}_2^{(k)}(l_k)}} I([\mathcal{C}_\mathrm{S}^{(k)}(l_k), \mathrm{R}, \mathcal{C}_\mathrm{D}^{(k)}(l_k)]), \end{aligned} \tag{33}$$

Then each group sends the calculated mutual information $I([\mathcal{C}_\mathrm{S}^{(k)}(\hat{l}_k), \mathrm{R}, \mathcal{C}_\mathrm{D}^{(k)}(\hat{l}_k)])$ of (31) with (33) to the controlling node.

3) Based on the mutual information $\left\{I([\mathcal{C}_\mathrm{S}^{(k)}(\hat{l}_k), \mathrm{R}, \mathcal{C}_\mathrm{D}^{(k)}(\hat{l}_k)]) : k = 1, \cdots, \mathcal{K}\right\}$, the controlling node chooses a single best group $\mathcal{G}_{\hat{k}}$ such that the mutual information is maximized as follows:

$$\hat{k} = \arg \max_{k=1,\cdots,\mathcal{K}} I([\mathcal{C}_\mathrm{S}^{(k)}(\hat{l}_k), \mathrm{R}, \mathcal{C}_\mathrm{D}^{(k)}(\hat{l}_k)]). \tag{34}$$

4) The controlling node broadcasts the selected information $\hat{k}$ to all the groups, and only the selected group start communication from $\mathrm{S}_{\hat{l}_{\hat{k}}}^{(\hat{k})}$ to $\mathrm{D}_{\hat{l}_{\hat{k}}}^{(\hat{k})}$ with the help of R, $\mathrm{S}_{3-\hat{l}_{\hat{k}}}^{(\hat{k})}$, and $\mathrm{D}_{3-\hat{l}_{\hat{k}}}^{(\hat{k})}$.

C. Outage Probability of Group-Based Suboptimum End-to-End Transmission Strategy

In this subsection, we derive the outage probability and diversity order of the suboptimum end-to-end transmission strategy. We first present the outage probability in the following theorem.

Theorem 3: The *exact closed-form* outage probability $P_\mathrm{out}^\mathrm{Sub}(R)$ of the suboptimum end-to-end transmission strategy is given by

$$\begin{aligned} &P_\mathrm{out}^\mathrm{Sub}(R) \\ &= \prod_{k=1}^{\mathcal{K}} \Phi_k(R; \bar{\gamma}_{\mathrm{S}_1,\mathrm{R}}^{(k)}, \bar{\gamma}_{\mathrm{S}_2,\mathrm{R}}^{(k)}, \bar{\gamma}_{\mathrm{R},\mathrm{D}_1}^{(k)}, \bar{\gamma}_{\mathrm{R},\mathrm{D}_2}^{(k)}, \bar{\gamma}_{\mathrm{S}_1,\mathrm{S}_2}^{(k)}, \bar{\gamma}_{\mathrm{D}_1,\mathrm{D}_2}^{(k)}), \end{aligned} \tag{35}$$

where

$$\begin{aligned} &\Phi_k(R; \bar{\gamma}_{\mathrm{S}_1,\mathrm{R}}^{(k)}, \bar{\gamma}_{\mathrm{S}_2,\mathrm{R}}^{(k)}, \bar{\gamma}_{\mathrm{R},\mathrm{D}_1}^{(k)}, \bar{\gamma}_{\mathrm{R},\mathrm{D}_2}^{(k)}, \bar{\gamma}_{\mathrm{S}_1,\mathrm{S}_2}^{(k)}, \bar{\gamma}_{\mathrm{D}_1,\mathrm{D}_2}^{(k)}) \\ &= \begin{cases} \Xi_0(R; \bar{\gamma}_{\mathrm{S}_1,\mathrm{R}}^{(k)}) + \Xi_0(R; \bar{\gamma}_{\mathrm{R},\mathrm{D}_1}^{(k)}) \\ -\Xi_0(R; \bar{\gamma}_{\mathrm{S}_1,\mathrm{R}}^{(k)})\Xi_0(R; \bar{\gamma}_{\mathrm{R},\mathrm{D}_1}^{(k)}), & |\mathcal{G}_k| = 2, \\ P_\mathrm{out}^\mathrm{SJS}(R; \bar{\gamma}_{\mathrm{S}_1,\mathrm{R}}^{(k)}, \bar{\gamma}_{\mathrm{S}_2,\mathrm{R}}^{(k)}, \bar{\gamma}_{\mathrm{R},\mathrm{D}_1}^{(k)}, \bar{\gamma}_{\mathrm{R},\mathrm{D}_2}^{(k)}, \bar{\gamma}_{\mathrm{S}_1,\mathrm{S}_1}^{(k)}, \bar{\gamma}_{\mathrm{D}_1,\mathrm{D}_2}^{(k)}), \\ & |\mathcal{G}_k| = 4. \end{cases} \end{aligned} \tag{36}$$

Proof: Using (34) with (33) and (31), the outage probability $P_\mathrm{out}^\mathrm{Sub}(R)$ of the suboptimum end-to-end transmission strategy can be given by

$$\begin{aligned} P_\mathrm{out}^\mathrm{Sub}(R) &= \Pr\left[\max_{k=1,\cdots,\mathcal{K}} I([\mathcal{C}_\mathrm{S}^{(k)}(\hat{l}_k), \mathrm{R}, \mathcal{C}_\mathrm{D}^{(k)}(\hat{l}_k)]) < R\right] \\ &= \prod_{k=1}^{\mathcal{K}} \Pr\left[I([\mathcal{C}_\mathrm{S}^{(k)}(\hat{l}_k), \mathrm{R}, \mathcal{C}_\mathrm{D}^{(k)}(\hat{l}_k)]) < R\right]. \end{aligned} \tag{37}$$

When $|\mathcal{G}_k| = 2$, using [37, eq. (6.81)], it can be shown that $\Pr\left[I([\mathcal{C}_\mathrm{S}^{(k)}(\hat{l}_k), \mathrm{R}, \mathcal{C}_\mathrm{D}^{(k)}(\hat{l}_k)]) < R\right] = \Xi_0(R; \bar{\gamma}_{\mathrm{S}_1,\mathrm{R}}^{(k)}) + \Xi_0(R; \bar{\gamma}_{\mathrm{R},\mathrm{D}_1}^{(k)}) - \Xi_0(R; \bar{\gamma}_{\mathrm{S}_1,\mathrm{R}}^{(k)})\Xi_0(R; \bar{\gamma}_{\mathrm{R},\mathrm{D}_1}^{(k)})$, which is given by the first case of (36). Also, when $|\mathcal{G}_k| = 4$, it can be shown that $\Pr\left[I([\mathcal{C}_\mathrm{S}^{(k)}(\hat{l}_k), \mathrm{R}, \mathcal{C}_\mathrm{D}^{(k)}(\hat{l}_k)]) < R\right] = P_\mathrm{out}^\mathrm{SJS}(R; \bar{\gamma}_{\mathrm{S}_1,\mathrm{R}}^{(k)}, \bar{\gamma}_{\mathrm{S}_2,\mathrm{R}}^{(k)}, \bar{\gamma}_{\mathrm{R},\mathrm{D}_1}^{(k)}, \bar{\gamma}_{\mathrm{R},\mathrm{D}_2}^{(k)}, \bar{\gamma}_{\mathrm{S}_1,\mathrm{S}_1}^{(k)}, \bar{\gamma}_{\mathrm{D}_1,\mathrm{D}_2}^{(k)})$, which is given by the second case of (36). Therefore, one can obtain the outage probability of (35). □

In the following, we present diversity order of the suboptimum strategy.

Lemma 2: The suboptimum end-to-end transmission strategy achieves the full diversity order.

Proof: Using Lemma 1 and (36), it is obvious that the diversity order of $\mathcal{G}_k$ is either one when $|\mathcal{G}_k| = 2$ or two when

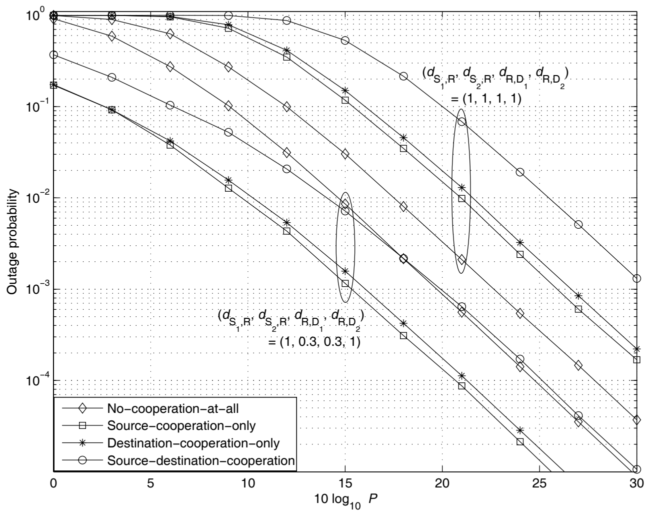


Fig. 5. Outage probabilities of the no-cooperation-at-all, source-cooperation-only, destination-cooperation-only, and source-destination-cooperation for two different channel settings: $(d_{\mathrm{S}_1,\mathrm{R}}, d_{\mathrm{S}_2,\mathrm{R}}, d_{\mathrm{R},\mathrm{D}_1}, d_{\mathrm{R},\mathrm{D}_2}) = (1,1,1,1)$ and $(1,0.3,0.3,1)$. $R = 1$ bps/Hz and $d_{\mathrm{S}_1,\mathrm{S}_2} = d_{\mathrm{D}_1,\mathrm{D}_2} = 0.2$.

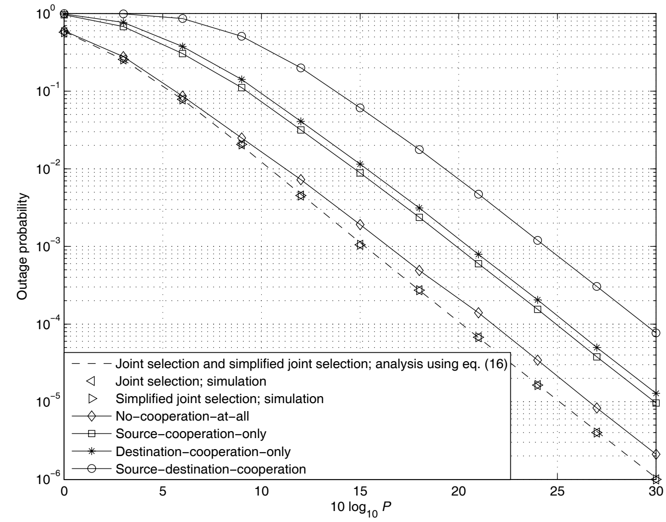


Fig. 6. Outage probabilities of the joint selection, simplified joint selection, and four end-to-end transmission strategies for a symmetric channel setting: $(d_{\mathrm{S}_1,\mathrm{R}}, d_{\mathrm{S}_2,\mathrm{R}}, d_{\mathrm{R},\mathrm{D}_1}, d_{\mathrm{R},\mathrm{D}_2}) = (0.7,0.7,0.7,0.7)$. $R = 1$ bps/Hz and $d_{\mathrm{S}_1,\mathrm{S}_2} = d_{\mathrm{D}_1,\mathrm{D}_2} = 0.2$.

$|\mathcal{G}_k| = 4$. Since the channels in one group are independent of the channels in other group, for L source-destination pairs, it can be shown that the diversity order of the suboptimum strategy is L. Therefore, the suboptimum strategy achieves the full diversity order. □

VI. Simulation Results

In this section, we check the accuracy of the obtained outage probability expressions by comparing Monte Carlo simulations. We let $d_{\mathrm{S}_l,\mathrm{R}}$ denote the distance between S_l and R; $d_{\mathrm{R},\mathrm{D}_l}$ denote the distance between D_l and R; $d_{\mathrm{S}_l,\mathrm{S}_k}$ denote the distance between S_l and S_k; and $d_{\mathrm{D}_l,\mathrm{D}_k}$ denote the distance between D_l and D_k, where $l, k = 1, \cdots, L$ and $k \neq l$. Furthermore, we set the path loss exponent as four to model radio propagation in urban areas [38]. As a result, we set $\Omega_{\mathrm{S}_l,\mathrm{R}} = d_{\mathrm{S}_l,\mathrm{R}}^{-4}$, $\Omega_{\mathrm{R},\mathrm{D}_l} = d_{\mathrm{R},\mathrm{D}_l}^{-4}$, $\Omega_{\mathrm{S}_l,\mathrm{S}_k} = d_{\mathrm{S}_l,\mathrm{S}_k}^{-4}$, and $\Omega_{\mathrm{D}_l,\mathrm{D}_k} = d_{\mathrm{D}_l,\mathrm{D}_k}^{-4}$.

A. For Two Source-Destination Pairs

In this subsection, we check the accuracy of the obtained outage probability expression in (16) for two source-destination pairs. We first compare the four end-to-end transmission strategies: no-cooperation-at-all, source-cooperation-only, destination-cooperation-only, and source-destination-cooperation. Fig. 5 shows the outage probabilities against $10\log_{10}\mathcal{P}$ of the four end-to-end transmission strategies for two different channel settings: $(d_{\mathrm{S}_1,\mathrm{R}}, d_{\mathrm{S}_2,\mathrm{R}}, d_{\mathrm{R},\mathrm{D}_1}, d_{\mathrm{R},\mathrm{D}_2}) = (1,1,1,1)$ and $(1,0.3,0.3,1)$, where we set $R = 1$ bps/Hz and $d_{\mathrm{S}_1,\mathrm{S}_2} = d_{\mathrm{D}_1,\mathrm{D}_2} = 0.2$. When $(d_{\mathrm{S}_1,\mathrm{R}}, d_{\mathrm{S}_2,\mathrm{R}}, d_{\mathrm{R},\mathrm{D}_1}, d_{\mathrm{R},\mathrm{D}_2}) = (1,1,1,1)$, we can see that the no-cooperation-at-all outperforms three other transmission strategies irrespective of SNR value. When $(d_{\mathrm{S}_1,\mathrm{R}}, d_{\mathrm{S}_2,\mathrm{R}}, d_{\mathrm{R},\mathrm{D}_1}, d_{\mathrm{R},\mathrm{D}_2}) = (1,0.3,0.3,1)$, however, we can see that the source-cooperation-only and destination-cooperation-only outperform two other transmission strategies. From Fig. 5, one can see that the four transmission strategies have different outage performance depending on channel conditions. Considering the number of time slots and transmission power, the no-cooperation-at-all always outperforms other three end-to-end transmission schemes for $Case\ k$, $k = 1,2,3,5,6,8,9,10$, of Table I. For $Case$ 4 and $Case$ 7, however, other three end-to-end transmission schemes may outperform the no-cooperation-at-all, because other three schemes may not in outage, whereas the no-cooperation-at-all is always in outage. Therefore, if either $Case$ 4 or $Case$ 7 does not occur frequently, then the no-cooperation-at-all outperforms other three end-to-end transmission schemes. For $(d_{\mathrm{S}_1,\mathrm{R}}, d_{\mathrm{S}_2,\mathrm{R}}, d_{\mathrm{R},\mathrm{D}_1}, d_{\mathrm{R},\mathrm{D}_2}) = (1,1,1,1)$, either $Case$ 4 or $Case$ 7 does not occur frequently, whereas for $(d_{\mathrm{S}_1,\mathrm{R}}, d_{\mathrm{S}_2,\mathrm{R}}, d_{\mathrm{R},\mathrm{D}_1}, d_{\mathrm{R},\mathrm{D}_2}) = (1,0.3,0.3,1)$, $Case$ 4 occurs frequently.

Secondly, we compare the joint selection, simplified joint selection, and four end-to-end transmission strategies in terms of SNR. Fig. 6 shows the outage probabilities against $10\log_{10}\mathcal{P}$ of the joint selection, simplified joint selection, and four end-to-end transmission strategies for a symmetric channel setting: $(d_{\mathrm{S}_1,\mathrm{R}}, d_{\mathrm{S}_2,\mathrm{R}}, d_{\mathrm{R},\mathrm{D}_1}, d_{\mathrm{R},\mathrm{D}_2}) = (0.7,0.7,0.7,0.7)$, where we set $R = 1$ bps/Hz and $d_{\mathrm{S}_1,\mathrm{S}_2} = d_{\mathrm{D}_1,\mathrm{D}_2} = 0.2$. Fig. 7 shows the outage probabilities against $10\log_{10}\mathcal{P}$ of the joint selection, simplified joint selection, and four end-to-end transmission strategies for an asymmetric channel setting: $(d_{\mathrm{S}_1,\mathrm{R}}, d_{\mathrm{S}_2,\mathrm{R}}, d_{\mathrm{R},\mathrm{D}_1}, d_{\mathrm{R},\mathrm{D}_2}) = (1,0.5,0.5,1)$, where we set $R = 1$ bps/Hz and $d_{\mathrm{S}_1,\mathrm{S}_2} = d_{\mathrm{D}_1,\mathrm{D}_2} = 0.2$. From Figs. 6 and 7, we can see the joint selection and simplified joint selection are identical, and (16) exactly matches with simulation results. Also, irrespective of SNR values, we can see that the joint selection and simplified joint selection outperform the four end-to-end transmission strategies.

Thirdly, we compare the joint selection, simplified joint selection, and four end-to-end transmission strategies in terms of distances. Fig. 8 shows the outage probabilities against $d_{\mathrm{S}_1,\mathrm{R}} = d_{\mathrm{S}_2,\mathrm{R}} = d_{\mathrm{R},\mathrm{D}_1} = d_{\mathrm{R},\mathrm{D}_2}$ of the joint selection,

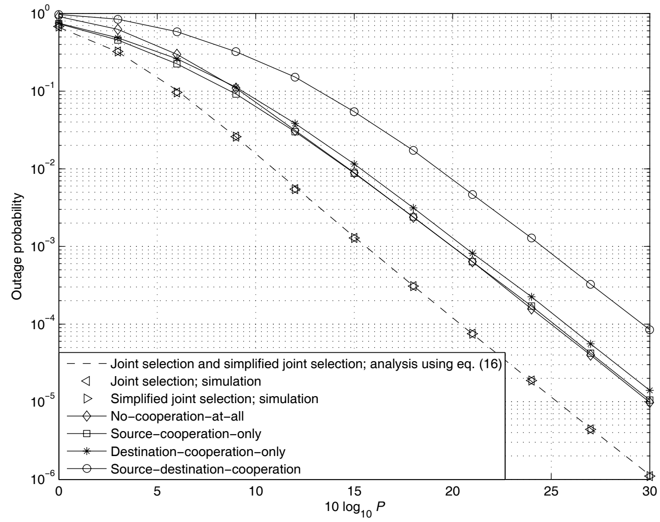


Fig. 7. Outage probabilities of the joint selection, simplified joint selection, and four end-to-end transmission strategies for an asymmetric channel setting: $(d_{\mathrm{S_1,R}}, d_{\mathrm{S_2,R}}, d_{\mathrm{R,D_1}}, d_{\mathrm{R,D_2}}) = (1, 0.5, 0.5, 1)$. $R = 1$ bps/Hz and $d_{\mathrm{S_1,S_2}} = d_{\mathrm{D_1,D_2}} = 0.2$.

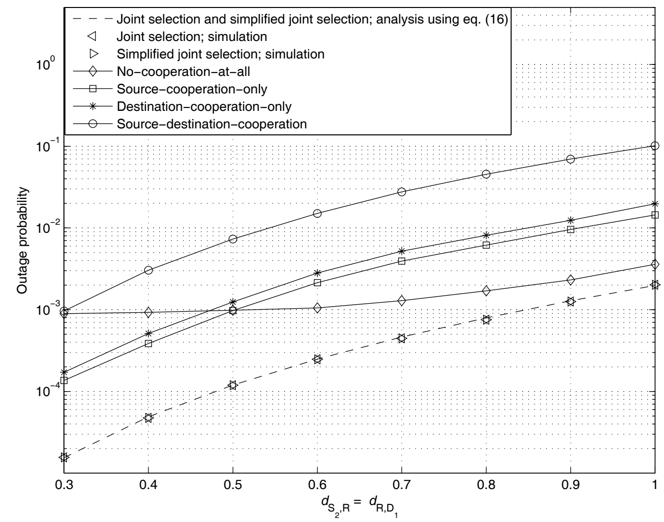


Fig. 9. Outage probabilities against $d_{\mathrm{S_2,R}} = d_{\mathrm{R,D_1}}$ of the joint selection, simplified joint selection, and four end-to-end transmission strategies. $R = 1$ bps/Hz, $10\log_{10}\mathcal{P} = 20$, $d_{\mathrm{S_1,R}} = d_{\mathrm{R,D_2}} = 1$, and $d_{\mathrm{S_1,S_2}} = d_{\mathrm{D_1,D_2}} = 0.2$.

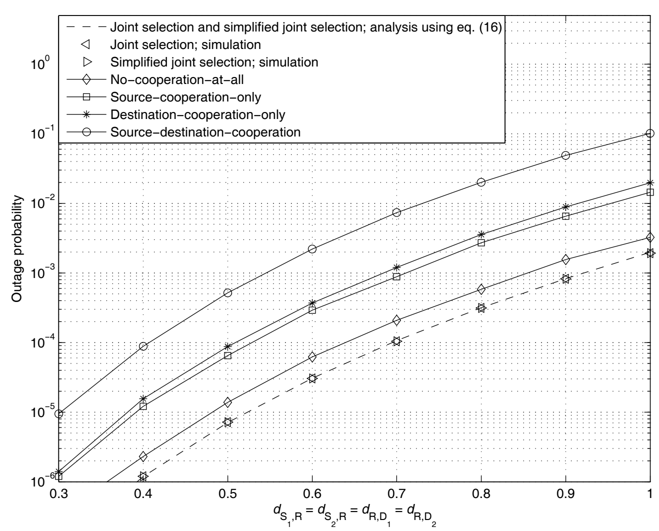


Fig. 8. Outage probabilities against $d_{\mathrm{S_1,R}} = d_{\mathrm{S_2,R}} = d_{\mathrm{R,D_1}} = d_{\mathrm{R,D_2}}$ of the joint selection, simplified joint selection, and four end-to-end transmission strategies. $R = 1$ bps/Hz, $10\log_{10}\mathcal{P} = 20$, and $d_{\mathrm{S_1,S_2}} = d_{\mathrm{D_1,D_2}} = 0.2$.

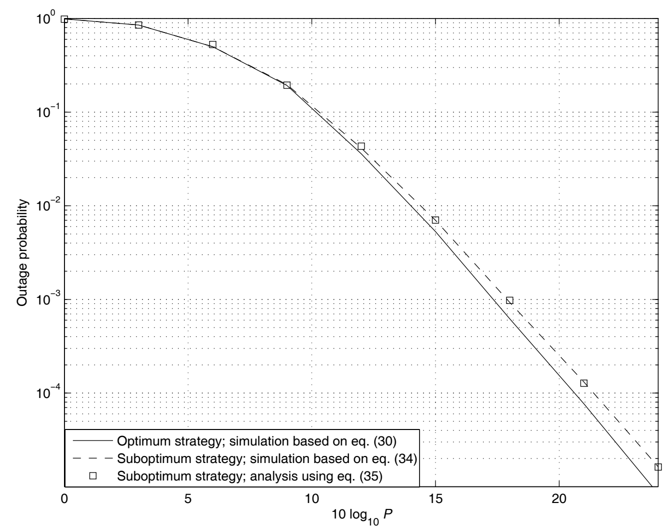


Fig. 10. Outage probabilities of the optimum strategy and suboptimum strategy for three source-destination pairs. $(d_{\mathrm{S_1,R}}, d_{\mathrm{S_2,R}}, d_{\mathrm{S_3,R}}, d_{\mathrm{R,D_1}}, d_{\mathrm{R,D_2}}, d_{\mathrm{R,D_3}}) = (1, 0.7, 1.2, 0.8, 1.5, 1.2)$, $(d_{\mathrm{S_1,S_2}}, d_{\mathrm{S_1,S_3}}, d_{\mathrm{S_2,S_3}}, d_{\mathrm{D_1,D_2}}, d_{\mathrm{D_1,D_3}}, d_{\mathrm{D_2,D_3}}) = (0.2, 0.6, 0.8, 1, 0.7, 1.2)$, and $R = 1$ bps/Hz.

simplified joint selection, and four end-to-end transmission strategies, where we set $R = 1$ bps/Hz, $10\log_{10}\mathcal{P} = 20$, and $d_{\mathrm{S_1,S_2}} = d_{\mathrm{D_1,D_2}} = 0.2$. Fig. 9 shows the outage probabilities against $d_{\mathrm{S_2,R}} = d_{\mathrm{R,D_1}}$ of the joint selection, simplified joint selection, and four end-to-end transmission strategies, where we set $R = 1$ bps/Hz, $10\log_{10}\mathcal{P} = 20$, $d_{\mathrm{S_1,R}} = d_{\mathrm{R,D_2}}$, and $d_{\mathrm{S_1,S_2}} = d_{\mathrm{D_1,D_2}} = 0.2$. From Figs. 6 and 7, we can see the joint selection and simplified joint selection are identical, and (16) exactly matches with simulation results. Also, irrespective of distances, we can see that the joint selection and simplified joint selection outperform the four end-to-end transmission strategies.

B. For Multiple Source-Destination Pairs

In this subsection, we compare the performance of the optimum and suboptimum strategies. For two source-destination pairs ($L = 2$), it is obvious that the optimum strategy is identical to the suboptimum strategy. For three source-destination pairs ($L = 3$), Fig. 10 shows the outage probabilities of the optimum strategy and suboptimum strategy, where we set $R = 1$ bps/Hz, $(d_{\mathrm{S_1,R}}, d_{\mathrm{S_2,R}}, d_{\mathrm{S_3,R}}, d_{\mathrm{R,D_1}}, d_{\mathrm{R,D_2}}, d_{\mathrm{R,D_3}}) = (1, 0.7, 1.2, 0.8, 1.5, 1.2)$, and $(d_{\mathrm{S_1,S_2}}, d_{\mathrm{S_1,S_3}}, d_{\mathrm{S_2,S_3}}, d_{\mathrm{D_1,D_2}}, d_{\mathrm{D_1,D_3}}, d_{\mathrm{D_2,D_3}}) = (0.2, 0.6, 0.8, 1, 0.7, 1.2)$. From Fig. 10, one can see that the outage performance gap between the optimum strategy and suboptimum strategy is small; specifically, the gap is as small as about 0.5 dB when the outage probability is 10^{-3}; and the outage analysis of the suboptimum strategy in (35) exactly matches with simulation results. For more than three source-destination pairs ($L \geq 4$), as we explained in Section V, due to the high signaling overhead and computational complexity, it is extremely difficult to implement the optimum strategy as is in practical systems. For example, if $L = 4$, there exist 1024 possibilities; if $L = 5$, there exist 21125 possibilities.

VII. Conclusions

We have combined source/destination cooperation and opportunistic transmission in a DF-based two-hop cooperative diversity network consisting of multiple source-destination pairs and one relay. Firstly, we have considered a scenario with two source-destination pairs. For this network, we have first considered four different end-to-end transmission strategies depending on the utilization of cooperation or not in each hop: no-cooperation-at-all, source-cooperation-only, destination-cooperation-only, and source-destination-cooperation. For each transmission strategy, we have selected a single best source-destination pair to maximize the mutual information, and we have found that the four transmission strategies complemented one another depending on channel conditions in terms of outage performance. Thus, we have proposed an optimum joint selection of source-destination pair and transmission strategy. Then we have shown that the optimum joint selection scheme could be simplified without loss of outage performance, and have derived its exact outage probability in closed-form. Secondly, we have generalized the proposed transmission strategy into a scenario with multiple source-destination pairs. For this network, we have first proposed an optimum end-to-end transmission strategy to maximize the mutual information, then a suboptimum end-to-end transmission strategy to reduce the signaling overhead and computational complexity. For the suboptimum strategy, we have derived the outage probability and diversity order.

Appendix A
Proof of Theorem 1

We will show the following relationship: $\epsilon\big[\max[\mathcal{I}_{2,l_{\mathrm{opt},2}}, \mathcal{I}_{3,l_{\mathrm{opt},3}}] < R\big] \subset \epsilon\big[\mathcal{I}_{4,l_{\mathrm{opt},4}} < R\big]$, which follows

$$\epsilon\big[\mathcal{I}_{1,l_{\mathrm{opt},1}} < R, \mathcal{I}_{2,l_{\mathrm{opt},2}} < R, \mathcal{I}_{3,l_{\mathrm{opt},3}} < R, \mathcal{I}_{4,l_{\mathrm{opt},4}} < R\big] = \epsilon\big[\mathcal{I}_{1,l_{\mathrm{opt},1}} < R, \mathcal{I}_{2,l_{\mathrm{opt},2}} < R, \mathcal{I}_{3,l_{\mathrm{opt},3}} < R\big], \tag{A.1}$$

where $\epsilon[\mathcal{U}]$ denotes an event $\mathcal{U}$. To this end, we first show that $\epsilon\big[\Gamma_{\max,1} < R_2\big] = \epsilon\big[\Gamma_{\max,2} < R_2\big]$, where $\Gamma_{\max,1} = \frac{3}{2}(2^{3\max[\mathcal{I}_{2,l_{\mathrm{opt},2}}, \mathcal{I}_{3,l_{\mathrm{opt},3}}]} - 1)$ and $\Gamma_{\max,2} = \frac{4}{2}(2^{4\mathcal{I}_{4,l_{\mathrm{opt},4}}} - 1)$. Using (8) and (9), one can obtain $\Gamma_{\max,1}$, which is given at the top of the next page. In (A.2), $Case\ A = \{\gamma_{\mathrm{S_1,S_2}} < R_2, \gamma_{\mathrm{R,D_1}} < R_2, \gamma_{\mathrm{R,D_2}} < R_2\}$, $Case\ B = \{\gamma_{\mathrm{S_1,S_2}} < R_2, \gamma_{\mathrm{R,D_1}} < R_2, \gamma_{\mathrm{R,D_2}} \geq R_2\}$, $Case\ C = \{\gamma_{\mathrm{S_1,S_2}} < R_2, \gamma_{\mathrm{R,D_1}} \geq R_2, \gamma_{\mathrm{R,D_2}} < R_2\}$, $Case\ D = \{\gamma_{\mathrm{S_1,S_2}} < R_2, \gamma_{\mathrm{R,D_1}} \geq R_2, \gamma_{\mathrm{R,D_2}} \geq R_2\}$, $Case\ E = \{\gamma_{\mathrm{S_1,S_2}} \geq R_2, \gamma_{\mathrm{R,D_1}} < R_2, \gamma_{\mathrm{R,D_2}} < R_2\}$, $Case\ F = \{\gamma_{\mathrm{S_1,S_2}} \geq R_2, \gamma_{\mathrm{R,D_1}} < R_2, \gamma_{\mathrm{R,D_2}} \geq R_2\}$, $Case\ G = \{\gamma_{\mathrm{S_1,S_2}} \geq R_2, \gamma_{\mathrm{R,D_1}} \geq R_2, \gamma_{\mathrm{R,D_2}} < R_2\}$, and $Case\ H = \{\gamma_{\mathrm{S_1,S_2}} \geq R_2, \gamma_{\mathrm{R,D_1}} \geq R_2, \gamma_{\mathrm{R,D_2}} \geq R_2\}$. Also, using (10), one can obtain $\Gamma_{\max,2}$, which is given at the top of the next page.

From (A.2) and (A.3), for $Case\ X$ with $X \in \{A, B, C, D, E\}$, one knows that the expressions of $\Gamma_{\max,1}$ and $\Gamma_{\max,2}$ are identical, which follows that $\epsilon\big[\Gamma_{\max,1} < R_2, Case\ X\big] = \epsilon\big[\Gamma_{\max,2} < R_2, Case\ X\big]$. Then we consider $Case\ F$. Since $\gamma_{\mathrm{R,D_2}} \geq R_2$, outage does not occur if $\gamma_{\mathrm{S_1,R}} + \gamma_{\mathrm{S_2,R}} \geq \gamma_{\mathrm{R,D_2}}$. Thus, the outage event $\epsilon\big[\Gamma_{\max,1} < R_2, Case\ F\big]$ is given by

$$\begin{aligned}\epsilon\big[\Gamma_{\max,1} < R_2, Case\ F\big] &= \epsilon\big[\max\big[\min[\gamma_{\mathrm{S_1,R}} + \gamma_{\mathrm{S_2,R}}, \gamma_{\mathrm{R,D_1}}],\\ &\qquad \min[\gamma_{\mathrm{S_1,R}}, \gamma_{\mathrm{R,D_1}} + \gamma_{\mathrm{D_1,D_2}}], \gamma_{\mathrm{S_1,R}} + \gamma_{\mathrm{S_2,R}}\big] < R_2,\\ &\qquad \gamma_{\mathrm{S_1,R}} + \gamma_{\mathrm{S_2,R}} < \gamma_{\mathrm{R,D_2}}, Case\ F\big].\end{aligned} \tag{A.4}$$

Considering the cases $\gamma_{\mathrm{S_1,R}} + \gamma_{\mathrm{S_2,R}} \gtrless \gamma_{\mathrm{R,D_1}}$ and $\gamma_{\mathrm{S_1,R}} \gtrless \gamma_{\mathrm{R,D_1}} + \gamma_{\mathrm{D_1,D_2}}$, it can be shown that

$$\max\big[\min[\gamma_{\mathrm{S_1,R}} + \gamma_{\mathrm{S_2,R}}, \gamma_{\mathrm{R,D_1}}], \min[\gamma_{\mathrm{S_1,R}}, \gamma_{\mathrm{R,D_1}} + \gamma_{\mathrm{D_1,D_2}}], \gamma_{\mathrm{S_1,R}} + \gamma_{\mathrm{S_2,R}}\big] = \gamma_{\mathrm{S_1,R}} + \gamma_{\mathrm{S_2,R}}. \tag{A.5}$$

Substituting (A.5) into (A.4), the outage event $\epsilon\big[\Gamma_{\max,1} < R_2, Case\ F\big]$ can be expressed by

$$\epsilon\big[\Gamma_{\max,1} < R_2, Case\ F\big] = \epsilon\big[\gamma_{\mathrm{S_1,R}} + \gamma_{\mathrm{S_2,R}} < R_2, \gamma_{\mathrm{S_1,R}} + \gamma_{\mathrm{S_2,R}} < \gamma_{\mathrm{R,D_2}}, Case\ F\big]. \tag{A.6}$$

Taking a step similar (A.4), the outage event $\epsilon\big[\Gamma_{\max,2} < R_2, Case\ F\big]$ can be given by

$$\begin{aligned}\epsilon\big[\Gamma_{\max,2} < R_2, Case\ F\big] &= \epsilon\big[\max\big[\min[\gamma_{\mathrm{S_1,R}} + \gamma_{\mathrm{S_2,R}}, \gamma_{\mathrm{R,D_1}} + \gamma_{\mathrm{D_1,D_2}}],\\ &\qquad \gamma_{\mathrm{S_1,R}} + \gamma_{\mathrm{S_2,R}}\big] < R_2,\\ &\qquad \gamma_{\mathrm{S_1,R}} + \gamma_{\mathrm{S_2,R}} < \gamma_{\mathrm{R,D_2}}, Case\ F\big].\end{aligned} \tag{A.7}$$

It can be shown that $\max[\min[\gamma_1, \gamma_2], \gamma_1] = \gamma_1$ for any γ_1 and γ_2. Then it is easy to see the outage event $\epsilon\big[\Gamma_{\max,2} < R_2, Case\ F\big]$ reduces to the right hand side of (A.6). Taking steps similar to those used from (A.4) to (A.7), one can easily show that $\epsilon\big[\Gamma_{\max,1} < R_2, Case\ G\big] = \epsilon\big[\Gamma_{\max,2} < R_2, Case\ G\big]$ and $\epsilon\big[\Gamma_{\max,1} < R_2, Case\ H\big] = \epsilon\big[\Gamma_{\max,2} < R_2, Case\ H\big]$. Therefore, one knows that $\epsilon\big[\Gamma_{\max,1} < R_2\big] = \epsilon\big[\Gamma_{\max,2} < R_2\big]$, which follows (A.1). Finally, from (A.1), it is obvious $P_{\mathrm{out}}^{\mathrm{SJS}}(R) = P_{\mathrm{out}}^{\mathrm{JS}}(R)$.

Appendix B
Proof of Theorem 2

We first consider the outage event $\epsilon\big[\mathcal{I}_{1,l_{\mathrm{opt},1}} < R\big]$ of the no-cooperation-at-all. In this strategy, as can be seen in (7), the outage status depends on only four values $(\gamma_{\mathrm{S_1,R}}, \gamma_{\mathrm{S_2,R}}, \gamma_{\mathrm{R,D_1}}, \gamma_{\mathrm{R,D_2}})$, and the status is given in Table I. Referring to Table I, we can rewrite the outage event $\epsilon\big[\mathcal{I}_{1,l_{\mathrm{opt},1}} < R\big]$ as follows:

$$\epsilon\big[\mathcal{I}_{1,l_{\mathrm{opt},1}} < R\big] = \epsilon\left[\bigcup_{k \in \{1,2,4,6,7,9\}} Case\ k\right], \tag{B.1}$$

$$\Gamma_{\max,1} = \begin{cases} \max\left[\min[\gamma_{S_1,R},\gamma_{R,D_1}],\min[\gamma_{S_2,R},\gamma_{R,D_2}]\right], & \textit{Case } A,\\ \max\left[\min[\gamma_{S_1,R},\gamma_{R,D_1}+\gamma_{D_1,D_2}],\min[\gamma_{S_2,R},\gamma_{R,D_2}]\right], & \textit{Case } B,\\ \max\left[\min[\gamma_{S_1,R},\gamma_{R,D_1}],\min[\gamma_{S_2,R},\gamma_{R,D_2}+\gamma_{D_1,D_2}]\right], & \textit{Case } C,\\ \max\left[\min[\gamma_{S_1,R},\gamma_{R,D_1}+\gamma_{D_1,D_2}],\min[\gamma_{S_2,R},\gamma_{R,D_2}+\gamma_{D_1,D_2}]\right], & \textit{Case } D,\\ \max\left[\min[\gamma_{S_1,R}+\gamma_{S_2,R},\gamma_{R,D_1}],\min[\gamma_{S_1,R}+\gamma_{S_2,R},\gamma_{R,D_2}]\right], & \textit{Case } E,\\ \max\left[\min[\gamma_{S_1,R}+\gamma_{S_2,R},\gamma_{R,D_1}],\min[\gamma_{S_1,R},\gamma_{R,D_1}+\gamma_{D_1,D_2}],\min[\gamma_{S_1,R}+\gamma_{S_2,R},\gamma_{R,D_2}]\right], & \textit{Case } F,\\ \max\left[\min[\gamma_{S_1,R}+\gamma_{S_2,R},\gamma_{R,D_1}],\min[\gamma_{S_1,R}+\gamma_{S_2,R},\gamma_{R,D_2}],\min[\gamma_{S_2,R},\gamma_{R,D_2}+\gamma_{D_1,D_2}]\right], & \textit{Case } G,\\ \max\left[\min[\gamma_{S_1,R}+\gamma_{S_2,R},\gamma_{R,D_1}],\min[\gamma_{S_1,R},\gamma_{R,D_1}+\gamma_{D_1,D_2}],\min[\gamma_{S_1,R}+\gamma_{S_2,R},\gamma_{R,D_2}],\right. & \\ \qquad \left.\min[\gamma_{S_2,R},\gamma_{R,D_2}+\gamma_{D_1,D_2}]\right], & \textit{Case } H, \end{cases} \quad \text{(A.2)}$$

$$\Gamma_{\max,2} = \begin{cases} \max\left[\min[\gamma_{S_1,R},\gamma_{R,D_1}],\min[\gamma_{S_2,R},\gamma_{R,D_2}]\right], & \textit{Case } A,\\ \max\left[\min[\gamma_{S_1,R},\gamma_{R,D_1}+\gamma_{D_1,D_2}],\min[\gamma_{S_2,R},\gamma_{R,D_2}]\right], & \textit{Case } B,\\ \max\left[\min[\gamma_{S_1,R},\gamma_{R,D_1}],\min[\gamma_{S_2,R},\gamma_{R,D_2}+\gamma_{D_1,D_2}]\right], & \textit{Case } C,\\ \max\left[\min[\gamma_{S_1,R},\gamma_{R,D_1}+\gamma_{D_1,D_2}],\min[\gamma_{S_2,R},\gamma_{R,D_2}+\gamma_{D_1,D_2}]\right], & \textit{Case } D,\\ \max\left[\min[\gamma_{S_1,R}+\gamma_{S_2,R},\gamma_{R,D_1}],\min[\gamma_{S_1,R}+\gamma_{S_2,R},\gamma_{R,D_2}]\right], & \textit{Case } E,\\ \max\left[\min[\gamma_{S_1,R}+\gamma_{S_2,R},\gamma_{R,D_1}+\gamma_{D_1,D_2}],\min[\gamma_{S_1,R}+\gamma_{S_2,R},\gamma_{R,D_2}]\right], & \textit{Case } F,\\ \max\left[\min[\gamma_{S_1,R}+\gamma_{S_2,R},\gamma_{R,D_1}],\min[\gamma_{S_1,R}+\gamma_{S_2},\gamma_{R,D_2}+\gamma_{D_1,D_2}]\right], & \textit{Case } G,\\ \max\left[\min[\gamma_{S_1,R}+\gamma_{S_2,R},\gamma_{R,D_1}+\gamma_{D_1,D_2}],\min[\gamma_{S_1,R}+\gamma_{S_2,R},\gamma_{R,D_2}+\gamma_{D_1,D_2}]\right], & \textit{Case } H, \end{cases} \quad \text{(A.3)}$$

where $\textit{Case } 1 = \{\gamma_{R,D_1} < R_1, \gamma_{R,D_2} < R_1\}$, $\textit{Case } 2 = \{\gamma_{S_1,R} < R_1, \gamma_{S_2,R} < R_1, \gamma_{R,D_1} < R_1, \gamma_{R,D_2} \geq R_1\}$, $\textit{Case } 4 = \{\gamma_{S_1,R} \geq R_1, \gamma_{S_2,R} < R_1, \gamma_{R,D_1} < R_1, \gamma_{R,D_2} \geq R_1\}$, $\textit{Case } 6 = \{\gamma_{S_1,R} < R_1, \gamma_{S_2,R} < R_1, \gamma_{R,D_1} \geq R_1, \gamma_{R,D_2} < R_1\}$, $\textit{Case } 7 = \{\gamma_{S_1,R} < R_1, \gamma_{S_2,R} \geq R_1, \gamma_{R,D_1} \geq R_1, \gamma_{R,D_2} < R_1\}$, and $\textit{Case } 9 = \{\gamma_{S_1,R} < R_1, \gamma_{S_2,R} < R_1, \gamma_{R,D_1} \geq R_1, \gamma_{R,D_2} \geq R_1\}$. Note that $\textit{Case } 1$ denotes the case when all the branches in the second hop, from R to D_1 and from R to D_2, are in outage; $\textit{Case } 2$, $\textit{Case } 6$, and $\textit{Case } 9$ denote the cases when all the branches in the first hop, from S_1 to R and from S_2 to R, are in outage; and $\textit{Case } 4$ ($\textit{Case } 7$) denotes the case when the second (first) hop of the link from S_1 via R to D_1 and the first (second) hop of the link from S_2 via R to D_2 are in outage.

Then we consider the outage event of the simplified joint selection. Since $\{\textit{Case } k : k \in \{1,2,4,6,7,9\}\}$ are disjoint one another, we can rewrite the outage event $\mathcal{E}_{\mathrm{SJS}}$ of the simplified joint selection as follows:

$$\mathcal{E}_{\mathrm{SJS}} = \bigcup_{k\in\{1,2,4,6,7,9\}} \mathcal{E}_k, \tag{B.2}$$

where $\mathcal{E}_k := \epsilon\left[\textit{Case } k \cap \left(\mathcal{I}_{2,l_{\mathrm{opt},2}} < R\right) \cap \left(\mathcal{I}_{3,l_{\mathrm{opt},3}} < R\right)\right]$. Then, using (B.2), we can obtain the outage probability $P_{\mathrm{out}}^{\mathrm{SJS}}(R)$ of the simplified joint selection as follows:

$$P_{\mathrm{out}}^{\mathrm{SJS}}(R) = \sum_{k\in\{1,2,4,6,7,9\}} \Pr[\mathcal{E}_k]. \tag{B.3}$$

In the following subsections, we derive $\Pr[\mathcal{E}_k]$ for $k \in \{1,2,4,6,7,9\}$.

1. Derivation of $\Pr[\mathcal{E}_k]$ *for* $k = 1,2,6,9$

Since $\gamma_{S_1,R} < R_1$, $\gamma_{S_2,R} < R_1$, and $\gamma_{R,D_1} < R_1$ for $\textit{Case } 2$, using (8) and (9), it can be shown that $\mathcal{I}_{2,1} < R$, $\mathcal{I}_{3,1} < R$, and $\mathcal{I}_{3,2} < R$. Also, since $\gamma_{S_2,R} < R_1$, $\gamma_{S_1,R} + \gamma_{S_2,R} < R_2$, and $2R_1 \leq R_2$, using (8), it can be shown that $\mathcal{I}_{2,2} < R$. In total, for $\textit{Case } 2$, it is always true that $\{\mathcal{I}_{j,l} < R : j = 2,3, l = 1,2\}$. Similarly, for $\textit{Case } 1$, $\textit{Case } 6$, and $\textit{Case } 9$, it can be shown that it is always true that $\{\mathcal{I}_{j,l} < R : j = 2,3, l = 1,2\}$. Therefore, we can obtain $\Pr[\mathcal{E}_k] = \Pr[\textit{Case } k]$ for $k = 1,2,6,9$. Since γ_{R,D_1} and γ_{R,D_2} are exponentially distributed random variables with mean $\bar{\gamma}_{R,D_1}$ and $\bar{\gamma}_{R,D_2}$, respectively, we can solve $\Pr[\mathcal{E}_1]$ as follows:

$$\begin{aligned}\Pr[\mathcal{E}_1] &= \left[\int_{x=0}^{R_1} f_{\gamma_{R,D_1}}(x)dx\right]\left[\int_{y=0}^{R_1} f_{\gamma_{R,D_2}}(y)dy\right]\\ &= \Xi_0(R_1;\bar{\gamma}_{R,D_1})\Xi_0(R_1;\bar{\gamma}_{R,D_2}),\end{aligned} \tag{B.4}$$

which is given in (17). Taking a step similar to (B.4), we can solve $\Pr[\mathcal{E}_2]$ in (18), $\Pr[\mathcal{E}_6]$ in (19), and $\Pr[\mathcal{E}_9]$ in (20).

2. Derivation of $\Pr[\mathcal{E}_k]$ *for* $k = 4,7$

Since $\gamma_{S_2,R} < R_1$ and $\gamma_{R,D_1} < R_1$ for $\textit{Case } 4$, using (8) and (9), it can be shown that $\mathcal{I}_{2,2} < R$ and $\mathcal{I}_{3,1} < R$. That is, for $\textit{Case } 4$, it is always true that $\{\mathcal{I}_{2,2} < R, \mathcal{I}_{3,1} < R\}$. Similarly, for $\textit{Case } 7$, it can be shown that it is always true that $\{\mathcal{I}_{2,1} < R, \mathcal{I}_{3,2} < R\}$. Therefore, we obtain the following relationships:

$$\Pr[\mathcal{E}_4] = \Pr\left[\textit{Case } 4, \max[\mathcal{I}_{2,2},\mathcal{I}_{3,1}] < R\right], \tag{B.5}$$

$$\Pr[\mathcal{E}_7] = \Pr\left[\textit{Case } 7, \max[\mathcal{I}_{2,1},\mathcal{I}_{3,2}] < R\right]. \tag{B.6}$$

We first calculate $\Pr[\mathcal{E}_4]$. We let $\Gamma_{\max,4} = \frac{3}{2}(2^{3\max[\mathcal{I}_{2,2},\mathcal{I}_{3,1}]} - 1)$. Since $\gamma_{S_1,R} \geq \gamma_{R,D_1}$ and $\gamma_{S_2,R} \leq \gamma_{R,D_2}$ for $\textit{Case } 4$, it is obvious that $\min[\gamma_{S_1,R},\gamma_{R,D_1}] = \gamma_{R,D_1}$ and $\min[\gamma_{S_2,R},\gamma_{R,D_2}] = \gamma_{S_2,R}$. Then, using (8) and (9), one can calculate the term $\Gamma_{\max,4}$, which is given at the top of the next page.

Substituting (B.7) into (B.5), we can rewrite $\Pr[\mathcal{E}_4]$ as follows

$$\begin{aligned}\Pr[\mathcal{E}_4] &= \Pr\left[\textit{Case } 4, \Gamma_{\max,4} < R_2\right]\\ &=: P_{\mathrm{out},\mathcal{E}_4}(1) + P_{\mathrm{out},\mathcal{E}_4}(2) + P_{\mathrm{out},\mathcal{E}_4}(3) + P_{\mathrm{out},\mathcal{E}_4}(4),\end{aligned} \tag{B.8}$$

where $P_{\text{out},\mathcal{E}_4}(1) = \Pr\big[Case\ 4, \gamma_{\text{S}_1,\text{S}_2} < R_2, \gamma_{\text{R},\text{D}_2} < R_2, \max[\gamma_{\text{R},\text{D}_1}, \gamma_{\text{S}_2,\text{R}}] < R_2\big]$, $P_{\text{out},\mathcal{E}_4}(2) = \Pr\big[Case\ 4, \gamma_{\text{S}_1,\text{S}_2} \geq R_2, \gamma_{\text{R},\text{D}_2} < R_2, \max\big[\gamma_{\text{R},\text{D}_1}, \min[\gamma_{\text{S}_1,\text{R}} + \gamma_{\text{S}_2,\text{R}}, \gamma_{\text{R},\text{D}_2}]\big] < R_2\big]$, $P_{\text{out},\mathcal{E}_4}(3) = \Pr\big[Case\ 4, \gamma_{\text{S}_1,\text{S}_2} < R_2, \gamma_{\text{R},\text{D}_2} \geq R_2, \max\big[\min[\gamma_{\text{S}_1,\text{R}}, \gamma_{\text{R},\text{D}_1} + \gamma_{\text{D}_1,\text{D}_2}], \gamma_{\text{S}_2,\text{R}}\big] < R_2\big]$, and $P_{\text{out},\mathcal{E}_4}(4) = \Pr\big[Case\ 4, \gamma_{\text{S}_1,\text{S}_2} \geq R_2, \gamma_{\text{R},\text{D}_2} \geq R_2, \max\big[\min[\gamma_{\text{S}_1,\text{R}}, \gamma_{\text{R},\text{D}_1} + \gamma_{\text{D}_1,\text{D}_2}], \min[\gamma_{\text{S}_1,\text{R}} + \gamma_{\text{S}_2,\text{R}}, \gamma_{\text{R},\text{D}_2}]\big] < R_2\big]$.

First, we derive the probability $P_{\text{out},\mathcal{E}_4}(1)$ in (B.8). Since $\gamma_{\text{R},\text{D}_1} < R_1$ and $\gamma_{\text{S}_2,\text{R}} < R_1$ for $Case$ 4 and $R_1 \leq R_2$, the condition $\max[\gamma_{\text{R},\text{D}_1}, \gamma_{\text{S}_2,\text{R}}] < R_2$ is always true. Thus, the probability $P_{\text{out},\mathcal{E}_4}(1)$ in (B.8) can be rewritten as

$$\begin{aligned} P_{\text{out},\mathcal{E}_4}(1) &= \Pr\big[Case\ 4, \gamma_{\text{S}_1,\text{S}_2} < R_2, \gamma_{\text{R},\text{D}_2} < R_2\big] \\ &= \Pr\big[\gamma_{\text{S}_1,\text{R}} \geq R_1, \gamma_{\text{S}_2,\text{R}} < R_1, \gamma_{\text{R},\text{D}_1} < R_1, \\ &\qquad R_1 \leq \gamma_{\text{R},\text{D}_2} < R_2, \gamma_{\text{S}_1,\text{S}_2} < R_2\big] \\ &= \Xi_1(R_1; \bar{\gamma}_{\text{S}_1,\text{R}})\Xi_0(R_1; \bar{\gamma}_{\text{S}_2,\text{R}})\Xi_0(R_1; \bar{\gamma}_{\text{R},\text{D}_1}) \\ &\quad \times \Xi_0(R_2; \bar{\gamma}_{\text{S}_1,\text{S}_2})\Xi_2(R_2, R_1; \bar{\gamma}_{\text{R},\text{D}_2}). \end{aligned} \tag{B.9}$$

Secondly, we derive the probability $P_{\text{out},\mathcal{E}_4}(2)$ in (B.8). For two independent random variables a and b and $R_1 \leq R_2$, it can be shown that $\Pr\big[a < R_1, \max[a, b] < R_2\big] = \Pr\big[a < R_1, b < R_2\big]$. Thus, the probability $P_{\text{out},\mathcal{E}_4}(2)$ in (B.8) can be given by

$$\begin{aligned} P_{\text{out},\mathcal{E}_4}(2) = \Pr\big[&Case\ 4, \gamma_{\text{S}_1,\text{S}_2} \geq R_2, \gamma_{\text{R},\text{D}_2} < R_2, \\ &\min[\gamma_{\text{S}_1,\text{R}} + \gamma_{\text{S}_2,\text{R}}, \gamma_{\text{R},\text{D}_2}] < R_2\big]. \end{aligned} \tag{B.10}$$

In the above equation, since $\gamma_{\text{R},\text{D}_2} < R_2$, the condition $\min[\gamma_{\text{S}_1,\text{R}} + \gamma_{\text{S}_2,\text{R}}, \gamma_{\text{R},\text{D}_2}] < R_2$ is always true. Thus, the probability $P_{\text{out},\mathcal{E}_4}(2)$ in (B.10) can be rewritten as

$$\begin{aligned} P_{\text{out},\mathcal{E}_4}(2) &= \Pr\big[Case\ 4, \gamma_{\text{S}_1,\text{S}_2} \geq R_2, \gamma_{\text{R},\text{D}_2} < R_2\big] \\ &= \Xi_1(R_1; \bar{\gamma}_{\text{S}_1,\text{R}})\Xi_0(R_1; \bar{\gamma}_{\text{S}_2,\text{R}})\Xi_0(R_1; \bar{\gamma}_{\text{R},\text{D}_1}) \\ &\quad \times \Xi_1(R_2; \bar{\gamma}_{\text{S}_1,\text{S}_2})\Xi_2(R_2, R_1; \bar{\gamma}_{\text{R},\text{D}_2}). \end{aligned} \tag{B.11}$$

Thirdly, we derive the probability $P_{\text{out},\mathcal{E}_4}(3)$ in (B.8). Taking a step similar to (B.10), we can rewrite the probability $P_{\text{out},\mathcal{E}_4}(3)$ in (B.8) as follows:

$$\begin{aligned} P_{\text{out},\mathcal{E}_4}(3) &= \Pr\big[Case\ 4, \gamma_{\text{S}_1,\text{S}_2} < R_2, \gamma_{\text{R},\text{D}_2} \geq R_2, \\ &\qquad \min[\gamma_{\text{S}_1,\text{R}}, \gamma_{\text{R},\text{D}_1} + \gamma_{\text{D}_1,\text{D}_2}] < R_2\big] \\ &= \Pr[\gamma_{\text{S}_2,\text{R}} < R_1]\Pr[\gamma_{\text{R},\text{D}_2} \geq R_2]\Pr[\gamma_{\text{S}_1,\text{S}_2} < R_2] \\ &\quad \times \Pr\big[\gamma_{\text{S}_1,\text{R}} \geq R_1, \gamma_{\text{R},\text{D}_1} < R_1, \\ &\qquad \min[\gamma_{\text{S}_1,\text{R}}, \gamma_{\text{R},\text{D}_1} + \gamma_{\text{D}_1,\text{D}_2}] < R_2\big]. \end{aligned} \tag{B.12}$$

For two independent random variables a and b, it can be shown that

$$\begin{aligned} \Pr\big[\min[a, b] < \bar{R}\big] &= \Pr[a < \bar{R}] + \Pr[b < \bar{R}] \\ &\quad - \Pr[a < \bar{R}]\Pr[b < \bar{R}]. \end{aligned} \tag{B.13}$$

To solve the probability $\Pr\big[\gamma_{\text{S}_1,\text{R}} \geq R_1, \gamma_{\text{R},\text{D}_1} < R_1, \min[\gamma_{\text{S}_1,\text{R}}, \gamma_{\text{R},\text{D}_1} + \gamma_{\text{D}_1,\text{D}_2}] < R_2\big]$ in (B.12), we calculate the probability $\Pr[\gamma_{\text{R},\text{D}_1} < R_1, \gamma_{\text{R},\text{D}_1} + \gamma_{\text{D}_1,\text{D}_2} < R_2]$ as follows:

$$\begin{aligned} &\Pr[\gamma_{\text{R},\text{D}_1} < R_1, \gamma_{\text{R},\text{D}_1} + \gamma_{\text{D}_1,\text{D}_2} < R_2] \\ &= \int_{x=0}^{R_1}\int_{z=0}^{R_2-x} f_{\gamma_{\text{R},\text{D}_1}}(x) f_{\gamma_{\text{D}_1,\text{D}_2}}(z)\,dz\,dx \\ &= \Xi_4(R_2, R_1; \bar{\gamma}_{\text{R},\text{D}_1}, \bar{\gamma}_{\text{D}_1,\text{D}_2}). \end{aligned} \tag{B.14}$$

Using (B.13) with (B.14), we can rewrite the probability $P_{\text{out},\mathcal{E}_4}(3)$ in (B.12) as follows:

$$\begin{aligned} P_{\text{out},\mathcal{E}_4}(3) &= \Xi_0(R_1; \bar{\gamma}_{\text{S}_2,\text{R}})\Xi_1(R_2; \bar{\gamma}_{\text{R},\text{D}_2})\Xi_0(R_2; \bar{\gamma}_{\text{S}_1,\text{S}_2}) \\ &\quad \times \Xi_3(R_2, R_1; \bar{\gamma}_{\text{S}_1,\text{R}}, \bar{\gamma}_{\text{R},\text{D}_1}, \bar{\gamma}_{\text{D}_1,\text{D}_2}). \end{aligned} \tag{B.15}$$

Fourthly, we derive the probability $P_{\text{out},\mathcal{E}_4}(4)$ in (B.8). One can show the relationship of (B.16), which is given at the top of the next page.

Substituting (B.16) into (B.8), the probability $P_{\text{out},\mathcal{E}_4}(4)$ can be expressed by the sum of four probabilities. In the probability $P_{\text{out},\mathcal{E}_4}(4)$ in (B.8), since $\gamma_{\text{R},\text{D}_2} \geq R_2$, it can be shown that $\max[\gamma_{\text{S}_1,\text{R}}, \gamma_{\text{R},\text{D}_2}] \geq R_2$ and $\max[\gamma_{\text{R},\text{D}_1} + \gamma_{\text{D}_1,\text{D}_2}, \gamma_{\text{R},\text{D}_2}] \geq R_2$, which follows that the third and fourth probabilities are zeroes. Combining the first and second cases in (B.16), therefore, the probability $P_{\text{out},\mathcal{E}_4}(4)$ in (B.8) can be given by

$$\begin{aligned} &P_{\text{out},\mathcal{E}_4}(4) \\ &= \Pr\big[Case\ 4, \gamma_{\text{S}_1,\text{S}_2} \geq R_2, \gamma_{\text{R},\text{D}_2} \geq R_2, \gamma_{\text{S}_1,\text{R}} + \gamma_{\text{S}_2,\text{R}} < R_2\big] \\ &= \Pr[\gamma_{\text{R},\text{D}_1} < R_1]\Pr[\gamma_{\text{R},\text{D}_2} \geq R_2]\Pr[\gamma_{\text{S}_1,\text{S}_2} \geq R_2] \\ &\quad \times \Pr\big[\gamma_{\text{S}_1,\text{R}} \geq R_1, \gamma_{\text{S}_2,\text{R}} < R_1, \gamma_{\text{S}_1,\text{R}} + \gamma_{\text{S}_2,\text{R}} < R_2\big]. \end{aligned} \tag{B.17}$$

Since $2R_1 \leq R_2$, the probability $\Pr\big[\gamma_{\text{S}_1,\text{R}} \geq R_1, \gamma_{\text{S}_2,\text{R}} < R_1, \gamma_{\text{S}_1,\text{R}} + \gamma_{\text{S}_2,\text{R}} < R_2\big]$ in (B.17) can be given by

$$\begin{aligned} &\Pr\big[\gamma_{\text{S}_1,\text{R}} \geq R_1, \gamma_{\text{S}_2,\text{R}} < R_1, \gamma_{\text{S}_1,\text{R}} + \gamma_{\text{S}_2,\text{R}} < R_2\big] \\ &= \int_{y=0}^{R_2}\int_{x=R_1}^{R_2-y} f_{\gamma_{\text{S}_1,\text{R}}}(x) f_{\gamma_{\text{S}_2,\text{R}}}(y)\,dx\,dy \\ &= \Xi_5(R_2, R_1; \bar{\gamma}_{\text{S}_1,\text{R}}, \bar{\gamma}_{\text{S}_2,\text{R}}). \end{aligned} \tag{B.18}$$

Substituting $\Xi_5(R_2, R_1; \bar{\gamma}_{\text{S}_1,\text{R}}, \bar{\gamma}_{\text{S}_2,\text{R}})$ of (B.18) into (B.17) gives the probability $P_{\text{out},\mathcal{E}_4}(4)$ in (B.17) as follows:

$$\begin{aligned} P_{\text{out},\mathcal{E}_4}(4) &= \Xi_0(R_1; \bar{\gamma}_{\text{R},\text{D}_1})\Xi_1(R_2; \bar{\gamma}_{\text{R},\text{D}_2})\Xi_1(R_2; \bar{\gamma}_{\text{S}_1,\text{S}_2}) \\ &\quad \times \Xi_5(R_2, R_1; \bar{\gamma}_{\text{S}_1,\text{R}}, \bar{\gamma}_{\text{S}_2,\text{R}}). \end{aligned} \tag{B.19}$$

Finally, substituting (B.9), (B.11), (B.15), and (B.19) into (B.8) yields $\Psi_5(\bar{\gamma}_{\text{S}_1,\text{R}}, \bar{\gamma}_{\text{S}_2,\text{R}}, \bar{\gamma}_{\text{R},\text{D}_1}, \bar{\gamma}_{\text{R},\text{D}_2})$ in (21). Also, taking steps similar to those used above, one can obtain $\Pr[\mathcal{E}_{\mathcal{E}_7}] = \Psi_5(\bar{\gamma}_{\text{S}_2,\text{R}}, \bar{\gamma}_{\text{S}_1,\text{R}}, \bar{\gamma}_{\text{R},\text{D}_2}, \bar{\gamma}_{\text{R},\text{D}_1})$.

References

[1] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity, parts I, II," *IEEE Trans. Commun.*, vol. 51, pp. 1927–1948, Nov. 2003.

[2] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, pp. 3062–3080, Dec. 2004.

[3] T. Abe, H. Shi, T. Asai, and H. Yoshino, "Relay techniques for MIMO wireless networks with multiple source and destination pairs," *EURASIP J. Wireless Commun. and Networking*, vol. 2006, pp. 1–9, Apr. 2006.

[4] S. Fazeli-Dehkordy, S. Shahbazpanahi, and S. Gazor, "Multiple peer-to-peer communications using a network of relays," *IEEE Trans. Signal Process.*, vol. 57, pp. 3053–3062, Aug. 2009.

[5] L. Zhang and L. J. Cimini, "Cooperative network coding in selective decode-and-forward networks with multiple source-destination pairs," in *Proc. Inf. Sciences and Systems*, Mar. 2008, pp. 521–526.

[6] A. Bletsas, A. G. Dimitriou, and J. N. Sahalos, "Interference-limited opportunistic relaying with reactive sensing," *IEEE Trans. Wireless Commun.*, vol. 9, pp. 14–20, Jan. 2010.

[7] A. Høst-Madsen, "Capacity bounds for cooperative diversity," *IEEE Trans. Inf. Theory*, vol. 52, pp. 1522–1544, Apr. 2006.

$$\Gamma_{\max,4} = \begin{cases} \max\left[\gamma_{\mathrm{R,D_1}}, \gamma_{\mathrm{S_2,R}}\right], & \gamma_{\mathrm{S_1,S_2}} < R_2 \text{ and } \gamma_{\mathrm{R,D_2}} < R_2, \\ \max\left[\gamma_{\mathrm{R,D_1}}, \min[\gamma_{\mathrm{S_1,R}} + \gamma_{\mathrm{S_2,R}}, \gamma_{\mathrm{R,D_2}}]\right], & \gamma_{\mathrm{S_1,S_2}} \geq R_2 \text{ and } \gamma_{\mathrm{R,D_2}} < R_2, \\ \max\left[\min[\gamma_{\mathrm{S_1,R}}, \gamma_{\mathrm{R,D_1}} + \gamma_{\mathrm{D_1,D_2}}], \gamma_{\mathrm{S_2,R}}\right], & \gamma_{\mathrm{S_1,S_2}} < R_2 \text{ and } \gamma_{\mathrm{R,D_2}} \geq R_2, \\ \max\left[\min[\gamma_{\mathrm{S_1,R}}, \gamma_{\mathrm{R,D_1}} + \gamma_{\mathrm{D_1,D_2}}], \min[\gamma_{\mathrm{S_1,R}} + \gamma_{\mathrm{S_2,R}}, \gamma_{\mathrm{R,D_2}}]\right], & \gamma_{\mathrm{S_1,S_2}} \geq R_2 \text{ and } \gamma_{\mathrm{R,D_2}} \geq R_2. \end{cases} \tag{B.7}$$

$$\begin{aligned} &\max\left[\min[\gamma_{\mathrm{S_1,R}}, \gamma_{\mathrm{R,D_1}} + \gamma_{\mathrm{D_1,D_2}}], \min[\gamma_{\mathrm{S_1,R}} + \gamma_{\mathrm{S_2,R}}, \gamma_{\mathrm{R,D_2}}]\right] \\ &= \begin{cases} \gamma_{\mathrm{S_1,R}} + \gamma_{\mathrm{S_2,R}}, & \gamma_{\mathrm{S_1,R}} < \gamma_{\mathrm{R,D_1}} + \gamma_{\mathrm{D_1,D_2}} \text{ and } \gamma_{\mathrm{S_1,R}} + \gamma_{\mathrm{S_2,R}} < \gamma_{\mathrm{R,D_2}}, \\ \gamma_{\mathrm{S_1,R}} + \gamma_{\mathrm{S_2,R}}, & \gamma_{\mathrm{S_1,R}} \geq \gamma_{\mathrm{R,D_1}} + \gamma_{\mathrm{D_1,D_2}} \text{ and } \gamma_{\mathrm{S_1,R}} + \gamma_{\mathrm{S_2,R}} < \gamma_{\mathrm{R,D_2}}, \\ \max[\gamma_{\mathrm{S_1,R}}, \gamma_{\mathrm{R,D_2}}], & \gamma_{\mathrm{S_1,R}} < \gamma_{\mathrm{R,D_1}} + \gamma_{\mathrm{D_1,D_2}} \text{ and } \gamma_{\mathrm{S_1,R}} + \gamma_{\mathrm{S_2,R}} \geq \gamma_{\mathrm{R,D_2}}, \\ \max[\gamma_{\mathrm{R,D_1}} + \gamma_{\mathrm{D_1,D_2}}, \gamma_{\mathrm{R,D_2}}], & \gamma_{\mathrm{S_1,R}} \geq \gamma_{\mathrm{R,D_1}} + \gamma_{\mathrm{D_1,D_2}} \text{ and } \gamma_{\mathrm{S_1,R}} + \gamma_{\mathrm{S_2,R}} \geq \gamma_{\mathrm{R,D_2}}. \end{cases} \end{aligned} \tag{B.16}$$

[8] C. T. K. Ng, N. Jindal, A. J. Goldsmith, and U. Mitra, "Capacity gain from two-transmitter and two-receiver cooperation," *IEEE Trans. Inf. Theory*, vol. 53, pp. 3822–3827, Oct. 2007.

[9] I.-H. Wang and D. N. C. Tse, "Interference mitigation through limited receiver cooperation: symmetric case," in *Proc. Inf. Theory Workshop*, Oct. 2009, pp. 579–583.

[10] S. Mathur, L. Sankaranarayanan, and N. B. Mandayam, "Coalitional games in receiver cooperation for spectrum sharing," in *Proc. Inf. Sciences and Systems*, Mar. 2006, pp. 949–954.

[11] D. Tse and P. Viswanath, *Fundamentals of Wireless Communications*. Cambridge, MA: Cambridge University Press, 2005.

[12] P. Viswanath, D. Tse, and R. Laroia, "Opprotunistic beamforming using dumb antennas," *IEEE Trans. Inf. Theory*, vol. 48, pp. 1277–1294, June 2002.

[13] A. Bletsas, A. Khisti, D. P. Reed, and A. Lippman, "A simple cooperative diversity method based on network path selection," *IEEE J. Sel. Areas Commun.*, vol. 24, pp. 659–672, Mar. 2006.

[14] A. Bletsas, H. Shin, and M. Z. Win, "Cooperative communications with outage-optimal opportunistic relaying," *IEEE Trans. Wireless Commun.*, vol. 6, pp. 3450–3460, Sep. 2007.

[15] D. Gündüz and E. Erkip, "Opportunistic cooperation by dynamic resource allocation," *IEEE Trans. Wireless Commun.*, vol. 6, pp. 1446–1454, Apr. 2007.

[16] Y. Zou, B. Zheng, and J. Zhu, "Outage analysis of opportunistic cooperation over Rayleigh fading channels," *IEEE Trans. Wireless Commun.*, vol. 8, pp. 3077–3085, June 2009.

[17] Q. Zhang, Q. Chen, F. Yang, X. Shen, and Z. Niu, "Cooperative and opportunistic transmission for wireless ad hoc networks," *IEEE Network*, vol. 21, pp. 14–20, Jan./Feb. 2007.

[18] Z. Ding, Y. Gong, T. Ratnarajah, and C. F. N. Cowan, "On the performance of opportunistic cooperative wireless networks," *IEEE Trans. Commun.*, vol. 56, pp. 1236–1240, Aug. 2008.

[19] X. Zhang, Z. B. Lv, and W. Wang, "Performance analysis of multiuser diversity in MIMO systems with antenna selection," *IEEE Trans. Wireless Commun.*, vol. 7, pp. 15–21, Jan. 2008.

[20] Y. Jing and H. Jafarkhani, "Single and multiple relay selection schemes and their achievable diversity order," *IEEE Trans. Wireless Commun.*, vol. 7, pp. 1414–1423, Mar. 2009.

[21] S. Chen, W. Wang, and X. Zhang, "Performance analysis of multiuser diversity in cooperative multi-relay networks under Rayleigh-fading channels," *IEEE Trans. Wireless Commun.*, vol. 8, pp. 3415–3419, July 2009.

[22] E. S. Sousa, "The effect of clock and carrier frequency offsets on the performance of a direct-sequence spread-spectrum multiple-access system," *IEEE J. Sel. Areas Commun.*, vol. 8, pp. 580–587, May 1990.

[23] T. Wang, A. Cano, G. B. Giannakis, and J. N. Laneman, "High-performance cooperative demodulation with decode-and-forward relays," *IEEE Trans. Commun.*, vol. 55, pp. 1427–1438, July 2007.

[24] T. Wang, G. B. Giannakis, and R. Wang, "Smart regenerative relays for link-adaptive cooperative communications," *IEEE Trans. Commun.*, vol. 56, pp. 1950–1960, Nov. 2008.

[25] M. Ju and I.-M. Kim, "ML performance analysis of the decode-and-forward protocol in cooperative diversity networks," *IEEE Trans. Wireless Commun.*, vol. 8, pp. 3855–3867, July 2009.

[26] D. Chen and J. N. Laneman, "Modulation and demodulation for cooperative diversity in wireless systems," *IEEE Trans. Wireless Commun.*, vol. 5, pp. 1785–1794, July 2006.

[27] P. Liu and I.-M. Kim, "Average BER analysis for binary signallings in decode-and-forward dissimilar cooperative diversity networks," *IEEE Trans. Wireless Commun.*, vol. 8, pp. 3961–3968, Aug. 2009.

[28] M. Malkawi and I.-M. Kim, "Hard/soft detection with limited CSI for multi-hop systems," *IEEE Trans. Wireless Commun.*, vol. 8, pp. 3435–3441, July 2009.

[29] A. S. Avestimehr and D. N. C. Tse, "Outage capacity of the fading relay channel in the low-SNR regime," *IEEE Trans. Inf. Theory*, vol. 53, pp. 1401–1415, Apr. 2007.

[30] M. O. Hasna and M. S. Alouini, "Outage probability of multihop transmission over Nakagami fading channels," *IEEE Commun. Lett.*, vol. 7, pp. 216–218, May 2003.

[31] L. Yang, M. O. Hasna, and M. S. Alouini, "Average outage duration of multihop communication systems with regenerative relays," *IEEE Trans. Wireless Commun.*, vol. 4, pp. 1366–1371, July 2005.

[32] A. Goldsmith, *Wireless Communications*. Cambridge Univ. Press, 2005.

[33] O. Sahin, E. Erkip, and O. Simeone, "Interference channel with a relay: models, relaying strategies, bounds," in *Proc. Inf. Theory and Applications Workshop*, Feb. 2009, pp. 90–95.

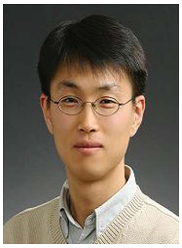
[34] I. Maric, R. Dabora, and A. Goldsmith, "An outer bound for the Gaussian interference channel with a relay," in *Proc. Inf. Theory Workshop*, Oct. 2009, pp. 569–573.

[35] I. Maric, A. Goldsmith, G. Kramer, and S. Shamai (Shitz), "On the capacity of interference channels with one cooperating transmitter," *European Trans. Telecommun.*, vol. 19, pp. 405–420, Apr. 2008.

[36] J. Rice, *Mathematical Statistics and Data Analysis*. Duxbury Press. 1999.

[37] A. Papoulis and S. U. Pillai, *Probability, Random Variables, and Stochastic Process*, 4th edition. New York: McGraw-Hill, 2002.

[38] T. S. Rappaport, *Wireless Communications: Principle and Practice*. Upper Saddle River, NJ: Prentice Hall, 2002.



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