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Research Article

Trust Degree-Based MISO Cooperative Communications with Two Relay Nodes

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In this paper, we propose transmission strategies in multiple-input-single-output (MISO) cooperative communications with two relay nodes in cases when the relay nodes have different trust degrees, where the trust degrees represent how much the relay nodes can be trusted for cooperation. For the given trust degrees and channel conditions, we first derive a relay selection strategy that maximizes the expected achievable rate. We then propose a cooperative transmission strategy of relays with an optimal cooperative beamforming vector that maximizes the expected achievable rate, which is a linear combination of weighted channel vectors. Finally, we derive the optimal transmission strategy, which is a mixed strategy between the relay selection and cooperative transmission strategies with respect to the trust degrees. Our analysis and numerical results show that the proposed transmission strategies increase the expected achievable rate by exploiting the trust degrees of the relay nodes, along with the channel conditions.

1. Introduction

Wireless mobile networks have been intensively investigated to satisfy the rapidly increasing demands for wireless mobile data traffic [1]. With the continuing development of mobile devices such as smartphones and tablet PCs, mobile users can easily communicate with their acquaintances via wireless devices. In recent years, the social relationships of users in mobile networks have emerged as an important issue due to the extensive communications between socially connected users. In existing mobile networks, the communication links are mainly developed based on physical parameters, e.g., physical distance, fading channels, and signal-to-noise power ratio (SNR). However, it may not be sufficient to only consider the quality of the physical links between the users. In cooperative communications using relays, for example, the transmitter can select the relay of the best channel quality expecting the highest transmission rate. However, in practice, it cannot be guaranteed that the selected relay will always help the transmitter; the selected relay may not be willing to forward the received data due to various social reasons such as selfishness to save its own resources, as well as malicious purposes like disconnecting the communications. Therefore, the social relationship between the nodes should be considered as a key design parameter for future mobile communications.

The social relationship has been considered in the various communication systems to develop communication strategies [2–11]. In [2, 3], a social group utility maximization (SGUM) game framework was proposed to proportionally maximize the utilities of socially connected users. The SGUM game takes into account the social tie, which quantifies the social closeness among the users, and each user in the game develops their own strategy so as to maximize the sum of individual utilities weighted by social ties. In the SGUM game framework, the authors of [2] proposed the power and random access control strategies and the authors of [3] proposed the distributed spectrum access algorithm. In [4, 5], the social relationship has also been considered for device-to-device (D2D) communication networks. By exploring the characteristics of the social relationship, the authors of [4] proposed a social-aware D2D communication architecture. In [5], the concept of social reciprocity, which is achieved through the exchange of altruistic actions among mobile users, was introduced, and the D2D relay selection strategy was developed based on social reciprocity.

The social relationship aware content caching strategies were also proposed for wireless caching networks [6–9]. Efficient content caching strategies were developed based on the social distance which considers social closeness as well as physical distance [6, 7] and the interest similarity of users [8, 9]. For confidential communications, transmission strategies that exploit the trustworthiness of nodes were proposed in [10]. In [10], in contrast to the existing schemes, which regard all other nodes in the system as an eavesdropper, the transmitter determines the risk of each node based on the trust degree and efficiently transmits the data with cooperation of the trustworthy nodes. The authors of [10] showed that the secrecy rate can be improved by exploiting the information regarding trustworthiness.

For multiple antenna systems, trust degree-based transmission strategies were proposed in [11–15]. In these works, the trust degree was considered as a parameter to quantify the social relationship. For a MISO cooperative communication system with a single relay, trust degree-based beamforming was proposed in [11]. The authors derived the expected achievable rate by taking into account the trust degree of the relay, and, by using the trust degree as a design parameter, the beamforming vector that maximizes the expected achievable rate was designed as a function of both the trust degrees and channel conditions. In [12], the authors proposed the beamforming design based on the trust degree of a relay for both half-duplex and full-duplex relay systems. The beamforming designed in [12] improves the performance of that in [11] in terms of the expected achievable rate by optimizing the probability to participate in the cooperative transmission. In [13], the trust degree-based user cooperation strategies were considered for various antenna configurations. The user with good physical channels can help the transmission of the other users according to the trust degree between the users. In this scenario, the trust degree-based power allocation and beamforming design were proposed. However, in the previous works, a simple trust model in which the relay nodes had the same trust degree was considered. Thus, only a single trust degree affected the transmission strategy design, so the effect of multiple trust degrees was not fully investigated.

In [14, 15], the authors considered multiple trust degrees in their system models. However, in these works, the trust degrees were simply used for an on-off concept as a threshold. The users who have trust degrees higher than the threshold are selected as the trustworthy users, so the users who have trust degrees lower than the threshold are filtered as the untrustworthy users. In [14], for a multiple-antenna system with multiple users, the multiuser computational offloading technique was investigated by combing the social trust degrees of the users. In [14], certain users were selected as trusted users based on their social trust degrees, and then the selected users were grouped into multiple pairs for the computational offloading. In this work, the social trust degrees were only used to filter out untrustworthy users and the conventional zero-forcing (ZF) beamformer was applied as the cooperative beamforming. In [15], the trust degree-based cooperative secure transmission strategy was proposed and evaluated in the stochastic geometry framework. In their proposed strategy, multiple users who have sufficiently high trust degrees cooperatively transmit data or jamming signals via virtual MISO channels among the users. In this work, similar to [14], the trust degree was used to select trustworthy users and filter out untrustworthy users. Hence, the relationship between multiple trust degrees was not fully exploited in designing the transmission strategy.

In this paper, we investigate the effects of the relays' multiple trust degrees on performance and propose relaying strategies with the corresponding beamformer design with respect to the various combinations of trust degrees. For the MISO cooperative communication systems with two relay nodes, we propose efficient transmission strategies that compositely exploit the physical characteristics (i.e., channel information and multiple antennas) and social characteristics (i.e., trust degrees of the relay nodes). We consider the trust degrees, which determine the relaying probabilities of the relay nodes, as the main design parameter. By taking into account the trust degrees, we explore three transmission strategies: (1) trust degree-based relay selection that allows transmitter (Tx) to select a single relay node to forward the data, (2) trust degree-based cooperative transmission of relays that allows two relay nodes to cooperatively forward the data, and (3) a mixed strategy between them. For the trust degree-based relay selection, we first define an expected achievable rate and categorize the selection strategy according to the trust degrees. For the cooperative transmission strategy, we derive a basic structure of the cooperative beamforming vector which maximizes the expected achievable rate as a linear combination of weighted channel vectors. We then obtain the cooperative beamforming vector as a closed form based on the basic structure. Furthermore, from the proposed transmission strategies, we find the optimal mixed transmission strategy in terms of the expected achievable rate according to the trust degrees of the relay nodes.

The rest of the paper is organized as follows. In Section 2, we first describe the concept of trust degree and our system model. We optimize the trust degree-based relay selection and cooperative transmission strategies in Sections 3 and 4, respectively. In Section 5, we find the optimal mixed transmission strategy between the trust degree-based relay selection and cooperative transmission strategies for the given trust degrees. In Section 6, we extend the proposed strategies to the relay systems with K relays. Section 7 numerically evaluates our proposed schemes, and Section 8 concludes our paper.

Notations. In this paper, a lowercase boldface letter represents a column vector (e.g., $\mathbf{x}$), and $(\cdot)^{\dagger}$ denotes a conjugate transpose (i.e., Hermitian). The notation $\|\mathbf{x}\|$ represents the Euclidean norm of a complex vector $\mathbf{x}$, and $|y|$ represents the magnitude of a complex number y. Also, $\Pi_{\mathbf{X}} \triangleq \mathbf{X}(\mathbf{X}^H\mathbf{X})^{-1}\mathbf{X}^H$ represents the projection onto the column space of $\mathbf{X}$, and

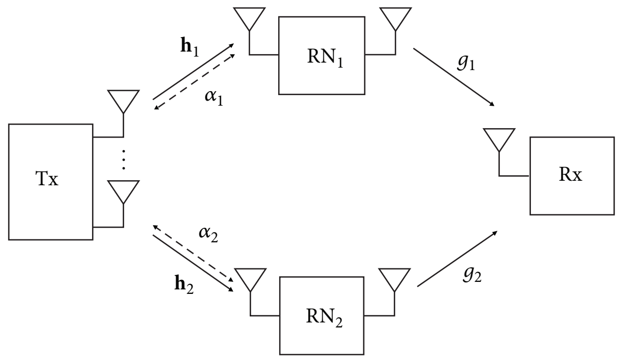

Figure 1: Physical and trust links of MISO cooperative communications with two relay nodes.

$\Pi_{\mathbf{X}}^{\perp} \triangleq \mathbf{I} - \Pi_{\mathbf{X}}$ represents the projection onto the null space of the column space of $\mathbf{X}$.

2. Problem Formulation

2.1. System Model. Our system model is illustrated in Figure 1. We consider a MISO cooperative communication system comprised of a transmitter (Tx), a receiver (Rx), and two relay nodes, where Tx has $M(\geq 2)$ transmit antennas, but Rx and the relay nodes have a single antenna. We assume that the direct channel from Tx to Rx is very weak to the point of being negligible, and hence Tx should be aided by relay nodes whenever it wants to communicate with Rx. For a relaying protocol, we consider half-duplex decode-and-forward (DF) relaying, where the relay node decodes Tx's data at the first phase and then forwards it to Rx in the second phase [16].

We assume that Tx and relay node i have the transmit power budgets P_T and P_i $(i = 1, 2)$, respectively, and Tx perfectly knows the channel state information (CSI) of the connected channel to relay node i denoted by $\mathbf{h}_i \in \mathbb{C}^M$ $(i = 1, 2)$. In this case, the channel is modeled as an $M \times 1$ circularly symmetric complex Gaussian vector whose elements are independent and identically distributed (i.i.d.) Gaussian random variables with zero means and variance $\sigma_{h_i}^2$, i.e., $\mathscr{CN}(0, \sigma_{h_i}^2)$. In the first phase, Tx transmits the data x to the relay nodes with the beamforming vector $\mathbf{w} \in \mathbb{C}^M$ such that $\|\mathbf{w}\|^2 \leq 1$. Then, the received signal at relay node i is given by

$$y_i = \sqrt{P_T}\mathbf{h}_i^{\dagger}\mathbf{w}x + n_i, \quad i \in \{1, 2\}, \tag{1}$$

where $n_i \in \mathbb{C}$ denotes an additive white Gaussian noise (AWGN) at relay node i, which follows $\mathscr{CN}(0, \sigma_{\mathrm{n}}^2)$, and $x \in \mathbb{C}$ is a transmitted symbol with transmit power P_T, i.e., $\mathbb{E}|x|^2 = P_T$.

In the conventional relaying protocols, it is generally assumed that a relay node always helps Tx's transmission, but this may not be true particularly when it is a personal device. Thus, in our system model, we consider the *trust degree* of relay nodes, which represents how favorably the relay nodes help Tx's transmission. We explain the trust degree in further detail in the next subsection.

2.2. Trust Degrees. In mobile social networks, a *trust degree* is defined as the belief level that one node holds in another node for a specific action, which can be found through direct/indirect information including observation [10, 17, 18]. A node with a high trust degree may believe that another node will act in a predefined way with a high probability [17]. From this definition, the trust degree of a node in a cooperative communication system reflects how willingly the node helps the other nodes' communication [10, 11]. Therefore, in our system model, we define the trust degree of each relay node as the probability that it will help Tx's transmission to Rx. We denote by α_i relay node i's trust degree such that $\alpha_1, \alpha_2 \in [0, 1]$.

In mobile social networks, the trust degree can be measured based on the previous behaviors of nodes [17, 19, 20]. One node measures the trust degree using either direct information from previous interactions of other nodes or indirect information from the accumulated observations of behaviors at the other nodes. Then, the measured trust degree can be updated according to the network transition and time. In [21], the trust degree is estimated using the Bayesian framework. In the Bayesian framework, the trust degree is defined by the ratio of the observed number of positive behaviors to the number of total observations. The *positive behavior* stands for that in which the node behaves in the predefined way of the network. Thus, similar to [21], the positive behavior can be defined by that in which the relay node helps the transmission from Tx to Rx in our cooperative communication system. Tx can estimate the trust degree of each relay node based on the accumulated observations of the positive behavior of the relay node. When the number of accumulated observations is sufficiently large, the trust degree will slowly change according to new observations. Therefore, we assume that the trust degree is a constant during the transmission.

2.3. Trust Degree-Based Transmission Strategies. In this paper, we propose three trust degree-based transmission strategies considering the relays' trust degrees and channel conditions as follows:

(1) *Trust degree-based relay selection strategy*. For the data transmission, Tx selects a single relay node, and the selected relay node forwards the received data from Tx to Rx according to trust degrees. In the relay selection strategy, Tx selects the relay node by considering the trust degrees of relay nodes as well as the channel conditions. We represent the relay selection strategy with beamforming vector $\mathbf{w}$ as $\mathscr{S}_{\mathrm{sel}}(\mathbf{w})$

(2) *Trust degree-based cooperative transmission strategy*. In the cooperative transmission, Tx transmits the data to both relay nodes, and then the relay nodes forward the received data to Rx with the cooperative transmission. In this strategy, whether or not the relay node participates in the cooperation is determined according to the trust degrees. We represent the cooperative transmission strategy with beamforming vector $\mathbf{w}$ as $\mathscr{S}_{\mathrm{co}}(\mathbf{w})$

(3) *Trust degree-based mixed strategy*. In this strategy, Tx chooses the best strategy between the trust degree-based relay selection and the cooperative transmission strategies considering both channel conditions and trust degrees

In the second phase, based on the transmission strategy, relay node i forwards the decoded data to Rx via relaying channel g_i, which follows a complex Gaussian distribution with zero mean and variance $\sigma_{g_i}^2$. In this phase, relay node i decides to forward the data received from Tx with probability α_i, which is the trust degree between Tx and relay node i. Considering all of the channel conditions and trust degrees, the expected achievable rate of the transmission strategy $\mathcal{S}(\mathbf{w}) \in \{\mathcal{S}_{\mathrm{sel}}(\mathbf{w}), \mathcal{S}_{\mathrm{co}}(\mathbf{w})\}$ is represented by $\overline{R}(\mathcal{S}(\mathbf{w}))$.

In the following section, we analyze the expected achievable rates for transmission strategies as well as the corresponding beamforming vectors in order to maximize the expected achievable rate.

2.4. Problem Description. For the given channel conditions and trust degrees, the optimal transmission strategy and the corresponding beamforming vector that maximize the expected achievable rate are obtained by solving the following problem:

$$\mathbf{P}: \underset{\mathcal{S}(\mathbf{w})}{\text{maximize}} \quad \overline{R}(\mathcal{S}(\mathbf{w})) \tag{2}$$

$$\text{subject to} \quad \|\mathbf{w}\|^2 \le 1, \tag{3a}$$

$$\mathcal{S}(\mathbf{w}) \in \{\mathcal{S}_{\mathrm{sel}}(\mathbf{w}), \mathcal{S}_{\mathrm{co}}(\mathbf{w})\}. \tag{3b}$$

In the following sections, we first derive the trust degree-based relay selection and the cooperative transmission strategies with corresponding beamforming vectors, respectively. Then, in order to maximize the expected achievable rate, we find the optimal mixed transmission strategy between the relay selection and the cooperative transmission strategies in terms of trust degrees.

3. Proposed Strategy 1: Trust Degree-Based Relay Selection Strategy

We first propose the trust degree-based relay selection strategy, where Tx selects a single relay node to forward the data to Rx. In the first phase, the achievable rate with the selection of relay node i is given by

$$R_i^{[1]}(\mathbf{w}) = \log\left(1 + \rho_T \left|\mathbf{h}_i^\dagger \mathbf{w}\right|^2\right), \tag{4}$$

where ρ_T is transmit SNR given by $\rho_T = P_T/\sigma_{\mathrm{n}}^2$.

In this strategy, since only a single relay node is selected, the beamforming vector for the relay selection maximizes the achievable rate between Tx and the selected relay node. When Tx selects relay node i, the beamforming vector that maximizes (4) becomes the maximum ratio transmission (MRT) beamforming vector given by

$$\mathbf{w}_i^{\mathrm{MRT}} = \frac{\mathbf{h}_i}{\|\mathbf{h}_i\|}, \quad i \in \{1, 2\}, \tag{5}$$

and hence we can represent the relay selection strategy as $\mathcal{S}_{\mathrm{sel}}(\mathbf{w}_i^{\mathrm{MRT}})$.

When Tx exploits relay node i with the beamforming vector $\mathbf{w}_i^{\mathrm{MRT}}$, the achievable rate at the first phase becomes

$$\begin{aligned} R_i^{[1]}\left(\mathbf{w}_i^{\mathrm{MRT}}\right) &= \log\left(1 + \rho_T \left|\mathbf{h}_i^\dagger \mathbf{w}_i^{\mathrm{MRT}}\right|^2\right) \\ &= \log\left(1 + \rho_T \|\mathbf{h}_i\|^2\right), \quad i \in \{1, 2\}. \end{aligned} \tag{6}$$

In the second phase, relay node i forwards the received data with the probability of α_i, so the expected achievable rate when relay node i is selected becomes

$$\overline{R}_i^{[2]} = \alpha_i R_i^{[2]} = \alpha_i \log\left(1 + \rho_i |g_i|^2\right), \quad i \in \{1, 2\}, \tag{7}$$

where $R_i^{[2]}$ is the achievable rate from relay node i to Rx given by

$$R_i^{[2]} = \log\left(1 + \rho_i |g_i|^2\right), \quad i \in \{1, 2\}, \tag{8}$$

where $\rho_i = P_i/\sigma_{\mathrm{n}}^2$ is transmit SNR at relay node i and g_i is the channel between relay node i and Rx.

Since we consider the half-duplex DF relaying, based on the achievable rate of DF relaying [16], the expected achievable rate when relay node i is selected is defined by

$$\overline{R}\left(\mathcal{S}_{\mathrm{sel}}\left(\mathbf{w}_i^{\mathrm{MRT}}\right)\right) = \frac{1}{2}\min\left\{R_i^{[1]}\left(\mathbf{w}_i^{\mathrm{MRT}}\right), \overline{R}_i^{[2]}\right\}, \tag{9}$$

where the pre-log factor 1/2 comes from a transmission duty cycle loss in half-duplex relaying systems.

In the trust degree-based relay selection strategy, Tx selects a relay node that maximizes the expected achievable rate considering trust degrees as in (9), and hence the relay selection strategy can be represented by $\mathcal{S}_{\mathrm{sel}}(\mathbf{w}_{i^*}^{\mathrm{MRT}})$, where i^* is the index of the selected relay node. For the trust degree-based relay selection, we can represent the expected achievable rate as follows:

$$\begin{aligned} &\overline{R}\left(\mathcal{S}_{\mathrm{sel}}\left(\mathbf{w}_{i^*}^{\mathrm{MRT}}\right)\right) \\ &\quad = \max\left\{\overline{R}\left(\mathcal{S}_{\mathrm{sel}}\left(\mathbf{w}_1^{\mathrm{MRT}}\right)\right), \overline{R}\left(\mathcal{S}_{\mathrm{sel}}\left(\mathbf{w}_2^{\mathrm{MRT}}\right)\right)\right\}. \end{aligned} \tag{10}$$

For the given channel conditions, we provide the relay selection strategy that maximizes (10) with respect to the trust degrees α_1 and α_2. From (7) and (9), we can observe that the expected achievable rate is affected by α_1 and α_2.

When $\alpha_1 \ge R_1^{[1]}/R_1^{[2]}$, we have $R_1^{[1]}(\mathbf{w}_1^{\mathrm{MRT}}) \le \overline{R}_2^{[2]}$, and thus the expected achievable rate of relay node i is determined by

$$\begin{aligned} \overline{R}\left(\mathcal{S}_{\mathrm{sel}}\left(\mathbf{w}_1^{\mathrm{MRT}}\right)\right) &= \frac{1}{2}R_1^{[1]}\left(\mathbf{w}_1^{\mathrm{MRT}}\right) \\ &= \frac{1}{2}\log\left(1 + \rho_T \|\mathbf{h}_1\|^2\right). \end{aligned} \tag{11}$$

In this case, if $\alpha_2 \ge R_2^{[1]}/R_2^{[2]}$, the expected achievable rate of relay node 2 is determined by

$$\begin{aligned} \overline{R}\left(\mathcal{S}_{\mathrm{sel}}\left(\mathbf{w}_2^{\mathrm{MRT}}\right)\right) &= \frac{1}{2}R_2^{[1]}\left(\mathbf{w}_2^{\mathrm{MRT}}\right) \\ &= \frac{1}{2}\log\left(1 + \rho_T \|\mathbf{h}_2\|^2\right), \end{aligned} \tag{12}$$

Table 1: Trust degree-based relay selection strategy.

Condition 1	Condition 2	Condition 3	Selection Strategy
$\alpha_1 \geq \frac{R_1^{[1]}}{R_1^{[2]}}$	$\alpha_2 \geq \frac{R_2^{[1]}}{R_2^{[2]}}$	$\|\mathbf{h}_1\|^2 \geq \|\mathbf{h}_2\|^2$	$\mathcal{S}_{\text{sel}}(\mathbf{w}) = \mathcal{S}_{\text{sel}}(\mathbf{w}_1^{\text{MRT}})$
		$\|\mathbf{h}_1\|^2 < \|\mathbf{h}_2\|^2$	$\mathcal{S}_{\text{sel}}(\mathbf{w}) = \mathcal{S}_{\text{sel}}(\mathbf{w}_2^{\text{MRT}})$
	$\alpha_2 < \frac{R_2^{[1]}}{R_2^{[2]}}$	$\alpha_2 \geq \frac{R_1^{[1]}}{R_2^{[2]}}$	$\mathcal{S}_{\text{sel}}(\mathbf{w}) = \mathcal{S}_{\text{sel}}(\mathbf{w}_2^{\text{MRT}})$
		$\alpha_1 < \frac{R_1^{[1]}}{R_2^{[2]}}$	$\mathcal{S}_{\text{sel}}(\mathbf{w}) = \mathcal{S}_{\text{sel}}(\mathbf{w}_1^{\text{MRT}})$
$\alpha_1 < \frac{R_1^{[1]}}{R_1^{[2]}}$	$\alpha_2 \geq \frac{R_2^{[1]}}{R_2^{[2]}}$	$\alpha_1 \geq \frac{R_2^{[1]}}{R_1^{[2]}}$	$\mathcal{S}_{\text{sel}}(\mathbf{w}) = \mathcal{S}_{\text{sel}}(\mathbf{w}_1^{\text{MRT}})$
		$\alpha_1 < \frac{R_2^{[1]}}{R_1^{[2]}}$	$\mathcal{S}_{\text{sel}}(\mathbf{w}) = \mathcal{S}_{\text{sel}}(\mathbf{w}_2^{\text{MRT}})$
	$\alpha_2 < \frac{R_2^{[1]}}{R_2^{[2]}}$	$\frac{\alpha_1}{\alpha_2} \geq \frac{R_2^{[2]}}{R_1^{[2]}}$	$\mathcal{S}_{\text{sel}}(\mathbf{w}) = \mathcal{S}_{\text{sel}}(\mathbf{w}_1^{\text{MRT}})$
		$\frac{\alpha_1}{\alpha_2} < \frac{R_2^{[2]}}{R_1^{[2]}}$	$\mathcal{S}_{\text{sel}}(\mathbf{w}) = \mathcal{S}_{\text{sel}}(\mathbf{w}_2^{\text{MRT}})$

and, by comparing (11) and (12), we can observe that the expected achievable rate is independent of trust degrees. Thus, in this case, the relay selection strategy is to choose a relay node of a larger channel gain between relay node 1 and relay node 2.

On the other hand, when $\alpha_2 < R_2^{[1]}/R_2^{[2]}$, the expected achievable rate of relay node 2 is determined by

$$\overline{R}\left(\mathcal{S}_{\text{sel}}\left(\mathbf{w}_2^{\text{MRT}}\right)\right) = \frac{1}{2}\overline{R}_2^{[2]} = \frac{1}{2}\alpha_2 R_2^{[2]}. \tag{13}$$

In this case, by comparing (11) and (13), we can see that if $\alpha_2 \geq R_1^{[1]}/R_2^{[2]}$, relay node 2 maximizes the expected achievable rate (i.e., $\overline{R}(\mathcal{S}_{\text{sel}}(\mathbf{w}_1^{\text{MRT}})) \leq \overline{R}(\mathcal{S}_{\text{sel}}(\mathbf{w}_2^{\text{MRT}}))$) and vice versa. By considering all possible cases with trust degrees, the trust degree-based relay selection strategy that maximizes the expected achievable rate is summarized in Table 1.

Remark 1. From the trust degree-based relay selection summarized in Table 1, we first observe that when the relay nodes' trust degrees are sufficiently large such as $\alpha_1 \geq R_1^{[1]}/R_1^{[2]}$ and $\alpha_2 \geq R_2^{[1]}/R_2^{[2]}$, Tx can only select the relay node with the channel conditions. In this case, since the relay nodes are sufficiently trustworthy to forward the data, Tx does not need to consider the cases in which relay nodes drop the data, and Tx selects the relay similarly with the conventional relay selection without considering relay nodes' trust degrees.

By contrast, when the trust degrees of relay nodes are relatively small such as $\alpha_1 < R_1^{[1]}/R_1^{[2]}$ and $\alpha_2 < R_2^{[1]}/R_2^{[2]}$, the trust degree directly affects the expected achievable rate. Thus, in this case, the expected achievable rate is determined by both trust degrees and channel conditions. Therefore, in this case, Tx selects the relay with the ratios of trust degrees and achievable rates, which is mainly determined by the channel conditions rather than the absolute values of trust degrees.

4. Proposed Strategy 2: Trust Degree-Based Cooperative Transmission Strategy

When two relay nodes cooperatively help Tx's transmission, Tx transmits the data to the relay nodes by expecting them to forward it to Rx. In the first phase, since both relay nodes should be able to decode the received data, the achievable rate of the cooperative transmission should be the minimum of the achievable rates of relay nodes as follows:

$$R^{[1]}(\mathbf{w}) = \min\left\{R_1^{[1]}(\mathbf{w}), R_2^{[1]}(\mathbf{w})\right\} \tag{14}$$

$$= \min\left\{\log\left(1 + \rho_T\left|\mathbf{h}_1^{\dagger}\mathbf{w}\right|^2\right), \log\left(1 + \rho_T\left|\mathbf{h}_2^{\dagger}\mathbf{w}\right|^2\right)\right\}. \tag{15}$$

In the second phase, since relay nodes decide to forward the received data according to their trust degrees, we have four possible cases, which are (1) forwarding by both relay nodes, (2) forwarding by relay node 1 only, (3) forwarding by relay node 2 only, and (4) nonforwarding by relay nodes. Taking into account the probabilities of the four cases with corresponding achievable rates, the expected achievable rate of the cooperative transmission in the second phase is obtained by

$$\overline{R}^{[2]} = \alpha_1\alpha_2 R_{\text{co}}^{[2]} + \alpha_1\left(1 - \alpha_2\right)R_1^{[2]} + \left(1 - \alpha_1\right)\alpha_2 R_2^{[2]}, \tag{16}$$

where $R_{\mathrm{co}}^{[2]} = \log(1+\rho_1|g_1|^2+\rho_2|g_2|^2)$ and $R_i^{[2]}$ is given in (8). In (16), the first term denotes the expected rate for the case in which both relay nodes cooperatively forward the data to relay nodes. The second and third terms of (16) denote the expected rates with forwarding by relay node 1 only and by relay node 2 only, respectively. When neither of the relay nodes forwards the data, the achievable rate is zero, and hence this case does not affect the expected achievable rate.

Based on the achievable rate of the half-duplex DF relaying, the expected achievable rate with the cooperative transmission of relay nodes is given by

$$\overline{R}\left(\mathcal{S}_{\mathrm{co}}(\mathbf{w})\right) = \frac{1}{2}\min\left\{R^{[1]}(\mathbf{w}), \overline{R}^{[2]}\right\}. \tag{17}$$

In order to maximize the expected achievable rate of the cooperative transmission given in (17), the cooperative beamforming vector is obtained by

$$\begin{aligned}\mathbf{w}_{\mathrm{co}} &= \underset{\|\mathbf{w}\|^2\le 1}{\arg\max}\ \overline{R}\left(\mathcal{S}_{\mathrm{co}}(\mathbf{w})\right), \\ &= \underset{\|\mathbf{w}\|^2\le 1}{\arg\max}\ R^{[1]}(\mathbf{w}).\end{aligned} \tag{18}$$

For the given channel conditions, we define the constant numbers ν_1, ν_2, and ν_3 as follows:

$$\begin{aligned}\nu_1 &= \left\|\mathbf{h}_2\right\|^2, \\ \nu_2 &= \left\|\Pi_{\mathbf{h}_2}\mathbf{h}_1\right\|^2, \\ \nu_3 &= \left\|\Pi_{\mathbf{h}_2}^{\perp}\mathbf{h}_1\right\|^2.\end{aligned} \tag{19}$$

Then, the basic structure of the cooperative beamforming vector is obtained in the following lemma.

Lemma 2. *The cooperative beamforming vector that maximizes the expected achievable rate with the cooperative relay transmission can be represented by the linear combination given by*

$$\mathbf{w}_{\mathrm{co}} = \sqrt{\gamma_i}\mathbf{w}_i + \sqrt{(1-\gamma_i)}\mathbf{w}_i^{\perp}, \quad i \in \{1,2\}, \tag{20}$$

where γ_i is a real number ranged in $0 \le \gamma_i \le 1$ and

$$\begin{aligned}\mathbf{w}_i &= \frac{\Pi_{\mathbf{h}_{\bar{i}}}\mathbf{h}_i}{\left\|\Pi_{\mathbf{h}_{\bar{i}}}\mathbf{h}_i\right\|}, \\ \mathbf{w}_i^{\perp} &= \frac{\Pi_{\mathbf{h}_{\bar{i}}}^{\perp}\mathbf{h}_i}{\left\|\Pi_{\mathbf{h}_{\bar{i}}}^{\perp}\mathbf{h}_i\right\|}, \\ & i, \bar{i} \in \{1,2\}, \ \bar{i} \ne i.\end{aligned} \tag{21}$$

Proof. We can prove the structure of the cooperative beamforming vector given in (20) by contradiction similarly with [11]. In (15), since the first and the second terms have the same structure with respect to $\mathbf{w}$, it is enough to prove the case of $i=1$. We first assume that the beamforming vector that maximizes the expected achievable rate of the cooperative transmission is $\widehat{\mathbf{w}} \in \mathbb{C}^M$ such that $\widehat{\mathbf{w}} \ne \mathbf{w}_{\mathrm{co}}$. Then, we can represent $\widehat{\mathbf{w}}$ by the linear combination of M-orthonormal bases as follows:

$$\widehat{\mathbf{w}} = \sqrt{\epsilon_1}\mathbf{w}_1 + \sqrt{\epsilon_2}\mathbf{w}_1^{\perp} + \sqrt{\epsilon_3}\boldsymbol{\psi}_3 + \cdots + \sqrt{\epsilon_M}\boldsymbol{\psi}_M, \tag{22}$$

where $\mathbf{w}_1 \cdot \boldsymbol{\psi}_l = 0$, $\mathbf{w}_1^{\perp} \cdot \boldsymbol{\psi}_l = 0$, and $\boldsymbol{\psi}_l \cdot \boldsymbol{\psi}_k = 0$ $(l \ne k)$ for $l = 3,\dots,M$. The coefficient ϵ_l is a real value constant with $\epsilon_l \ne 0$ for any l, and $\sum_{l=1}^{M}\epsilon_l \le 1$. Substituting (22) into (15), $R^{[1]}(\widehat{\mathbf{w}})$ can be represented by

$$\begin{aligned}R^{[1]}(\widehat{\mathbf{w}}) = \min\Big\{&\log\left(1+\rho_T\left(\sqrt{\epsilon_1\nu_2}+\sqrt{\epsilon_2\nu_3}\right)^2\right), \\ &\log\left(1+\rho_T\epsilon_1\nu_1\right)\Big\}.\end{aligned} \tag{23}$$

We can define $\widetilde{\mathbf{w}}$ as

$$\widetilde{\mathbf{w}} = \sqrt{\epsilon_1}\mathbf{w}_1 + \sqrt{\widetilde{\epsilon}_2}\mathbf{w}_1^{\perp}, \tag{24}$$

where $\widetilde{\epsilon}_2 = \epsilon_2 + \ldots + \epsilon_M$. Then, we have $\|\widetilde{\mathbf{w}}\|^2 = \|\widehat{\mathbf{w}}\|^2$. By substituting (24) into (15), $R^{[1]}(\widetilde{\mathbf{w}})$ can be represented by

$$\begin{aligned}R^{[1]}(\widetilde{\mathbf{w}}) = \min\Big\{&\log\left(1+\rho_T\left(\sqrt{\epsilon_1\nu_2}+\sqrt{\widetilde{\epsilon}_2\nu_3}\right)^2\right), \\ &\log\left(1+\rho_T\epsilon_1\nu_1\right)\Big\}.\end{aligned} \tag{25}$$

Since $\widetilde{\epsilon}_2$ is larger than ϵ_2, by comparing to (23) and (25), we have

$$R^{[1]}(\widehat{\mathbf{w}}) \le R^{[1]}(\widetilde{\mathbf{w}}), \tag{26}$$

which violates the assumption that $\widehat{\mathbf{w}}$ maximizes the expected achievable rate. Also, if $\|\widetilde{\mathbf{w}}\|^2 = \beta$ such that $\beta < 1$, we can design the beamforming vector as $\widetilde{\mathbf{w}}' = \sqrt{1/\beta}\widetilde{\mathbf{w}}$, which satisfies $\|\widetilde{\mathbf{w}}'\|^2 = 1$. Then, $\widetilde{\mathbf{w}}'$ always increases the rate achieved by $\widetilde{\mathbf{w}}$. Thus, the cooperative beamforming vector should satisfy $\|\mathbf{w}_{\mathrm{co}}\|^2 = 1$. Therefore, the cooperative beamforming vector that maximizes the expected achievable rate of the cooperative transmission is represented by (20), which has $\epsilon_l = 0$ for $l = 3,\dots,M$. □

From Lemma 2, we can obtain the following corollary.

Corollary 3. *The cooperative beamforming vector can be represented by the linear combination of the MRT beamforming vectors of $\mathbf{h}_1$ and $\mathbf{h}_2$ as follows:*

$$\mathbf{w}_{\mathrm{co}} = \eta_1\mathbf{w}_1^{\mathrm{MRT}} + \eta_2\mathbf{w}_2^{\mathrm{MRT}}, \tag{27}$$

where η_1 and η_2 are selected to satisfy $\|\mathbf{w}_{\mathrm{co}}\|^2 = 1$.

Proof. The channel vector $\mathbf{h}_1$ can be represented by $\mathbf{h}_1 = \Pi_{\mathbf{h}_2}\mathbf{h}_1 + \Pi_{\mathbf{h}_2}^{\perp}\mathbf{h}_1$, and, with the scalar value ξ, we have $\mathbf{h}_2 = \xi\Pi_{\mathbf{h}_2}\mathbf{h}_1$. Hence, the cooperative beamforming vector in (20) can be represented by the linear combination of channel vectors $\mathbf{h}_1$ and $\mathbf{h}_2$. Since the MRT beamforming vectors are normalized vectors of channels, the cooperative beamforming vector in (20) can be represented by the linear combination of the MRT beamforming vectors of $\mathbf{h}_1$ and $\mathbf{h}_2$ as given in (27). □

From Corollary 3, we can observe that the cooperative beamforming vector has the structure of the linear combination of MRT beamforming vectors of $\mathbf{h}_1$ and $\mathbf{h}_2$, which are the normalized vectors of the channel directions. Therefore, we can interpret that the cooperative beamforming vector design is an optimally steered direction between directions of $\mathbf{h}_1$ and $\mathbf{h}_2$ to balance the achievable rates of both relay nodes.

Based on the structure of the cooperative beamforming vector derived in Lemma 2, in the following theorem, we obtain the cooperative beamforming vector that maximizes the expected achievable rate of cooperative transmission in a closed form.

Theorem 4. *The cooperative beamforming vector that maximizes the expected achievable rate of the cooperative transmission is obtained by*

$$\mathbf{w}_{\text{co}} = \sqrt{\gamma_1^*}\mathbf{w}_1 + \sqrt{(1-\gamma_1^*)}\mathbf{w}_1^{\perp}, \tag{28}$$

where

$$\gamma_1^* = \begin{cases} 1, & \text{if } \nu_1 < \nu_2 \\ \dfrac{\nu_2}{\nu_2+\nu_3}, & \text{if } \nu_1 > \dfrac{(\nu_1+\nu_3)^2}{\nu_2} \\ \gamma_{1,\text{eq}}, & \text{otherwise.} \end{cases} \tag{29}$$

In the equation above, ν_1, ν_2, and ν_3 are given in (19) and $\gamma_{1,\text{eq}}$ is given by

$$\gamma_{1,\text{eq}} = \frac{\nu_3\left(\nu_1+\nu_2+\nu_3+2\sqrt{\nu_1\nu_2}\right)}{(\nu_1+\nu_3)^2+\nu_3(\nu_1+\nu_2+\nu_3)}. \tag{30}$$

Proof. First, we define $f(\gamma_1)$ and $g(\gamma_1)$ as functions of γ_1 given by

$$f(\gamma_1) = \left(\sqrt{\gamma_1\nu_2} + \sqrt{(1-\gamma_1)\nu_3}\right)^2, \tag{31}$$

$$g(\gamma_1) = \gamma_1\nu_1. \tag{32}$$

From (31) and (32), we can check that $f(\gamma_1)$ is a concave function of γ_1 by the second-order derivative as follows:

$$\begin{aligned} \frac{\partial^2 f(\gamma_1)}{\partial\gamma_1^2} &= \frac{\partial^2\left(\sqrt{\gamma_1\nu_2}+\sqrt{(1-\gamma_1)\nu_3}\right)^2}{\partial\gamma_1^2} < 0 \\ &\Longrightarrow -\gamma_1^2(1-\gamma_1)^2\sqrt{\gamma_1\nu_2}\sqrt{(1-\gamma_1)\nu_3} < 0. \end{aligned} \tag{33}$$

Also, we can find that $g(\gamma_1)$ is an increasing function with respect to γ_1.

By substituting (20) into (15), $R^{[1]}(\mathbf{w}_{\text{co}})$ can be represented by the function of γ_1 as

$$\begin{aligned} &R^{[1]}(\gamma_1) \\ &\quad = \min\left\{\log(1+\rho_T f(\gamma_1)), \log(1+\rho_T g(\gamma_1))\right\}. \end{aligned} \tag{34}$$

When $\nu_1 < \nu_2$, we have $f(\gamma_1) > g(\gamma_1)$ for any γ_1 $(0 \le \gamma_1 \le 1)$. Thus, in order to maximize $R^{[1]}(\gamma_1) = \log(1+\rho_T g(\gamma_1))$, we obtain $\gamma_1^* = 1$, which is γ_1 that maximizes $g(\gamma_1)$.

On the other hand, when $\nu_1 > (\nu_1+\nu_3)^2/\nu_2$, we have $f(\gamma_1) < g(\gamma_1)$ for any γ_1 $(0 \le \gamma_1 \le 1)$. In this case, (34) is represented by $R^{[1]}(\gamma_1) = \log(1+\rho_T f(\gamma_1))$, and $R^{[1]}(\gamma_1)$ is a concave function with respect to γ_1. Thus, by solving $\partial R^{[1]}(\gamma_1)/\partial\gamma_1 = 0$, we obtain $\gamma_1^* = \nu_2/(\nu_2+\nu_3)$.

Otherwise, when $\nu_2 \le \nu_1 \le (\nu_1+\nu_3)^2/\nu_2$, $R^{[1]}(\gamma_1)$ can be represented by either $R^{[1]}(\gamma_1) = \log(1+\rho_T f(\gamma_1))$ or $R^{[1]}(\gamma_1) = \log(1+\rho_T g(\gamma_1))$ according to the value of γ_1. Thus, we consider the cases by dividing the range of γ_1 as $0 \le \gamma_1 \le \gamma_{1,\text{eq}}$ and $\gamma_{1,\text{eq}} \le \gamma_1 \le 1$, where $\gamma_{1,\text{eq}}$ in (30) is obtained to satisfy the following condition:

$$\log\left(1+\rho_T f\left(\gamma_{1,\text{eq}}\right)\right) = \log\left(1+\rho_T g\left(\gamma_{1,\text{eq}}\right)\right). \tag{35}$$

First, for γ_1 such that $0 \le \gamma_1 \le \gamma_{1,\text{eq}}$, the function $R^{[1]}(\gamma_1)$ is represented by $R^{[1]}(\gamma_1) = \log(1+\rho_T g(\gamma_1))$. In this range, since $R^{[1]}(\gamma_1)$ is the increasing function of γ_1, we obtain $\gamma_1^* = \gamma_{1,\text{eq}}$. For γ_1 such that $\gamma_{1,\text{eq}} \le \gamma_1 \le 1$, $R^{[1]}(\gamma_1)$ is represented by $R^{[1]}(\gamma_1) = \log(1+\rho_T f(\gamma_1))$, which is a concave function of γ_1. However, in this range, the critical point is smaller than or equal to $\gamma_{1,\text{eq}}$ such as $\nu_2/(\nu_2+\nu_3) < \gamma_{1,\text{eq}}$, and hence $R^{[1]}(\gamma_1)$ becomes the decreasing function of γ_1. Thus, we can obtain $\gamma_1^* = \gamma_{1,\text{eq}}$. Therefore, for both ranges, we obtain the coefficient γ_1^* that maximizes $R^{[1]}(\gamma_1)$ as $\gamma_1^* = \gamma_{1,\text{eq}}$. □

Remark 5. From Theorem 4, we can observe that when the channel gain of a relay node is relatively smaller than that of another relay node such as $\nu_1 < \nu_2$ or $\nu_1 > (\nu_1+\nu_3)^2/\nu_2$, the beamforming vector should be the MRT beamforming vector of the channel direction with a smaller channel gain. In contrast to the relay selection strategy, the cooperative beamforming vector is designed to maximize the achievable rate of the relay node with a smaller channel gain. Otherwise, for general cases, the cooperative beamforming vector should be designed so as to balance the achievable rates of two relay nodes. Thus, with the cooperative beamforming vector, the achievable rates of the relay nodes become the same, i.e., $R_1^{[1]}(\mathbf{w}_{\text{co}}) = R_2^{[1]}(\mathbf{w}_{\text{co}})$.

5. Proposed Strategy 3: Trust Degree-Based Mixed Strategy

In the previous sections, we proposed the trust degree-based relay selection and the cooperative transmission strategies and found the corresponding beamforming vectors that maximize the expected achievable rates for the strategies. In this section, using the proposed strategies, we obtain the optimal mixed strategy that maximizes the expected achievable rate in terms of trust degrees.

In the following theorem, we derive the optimal mixed strategy and corresponding beamforming vector in order to maximize the expected achievable rate according to trust degrees.

Theorem 6. *For the given trust degrees, the optimal transmission strategy and corresponding beamforming vector that maximize the expected achievable rate are given by*

$$\mathcal{S}_{\text{opt}}\left(\mathbf{w}_{\text{opt}}\right) = \begin{cases} \mathcal{S}_{\text{co}}\left(\mathbf{w}_{\text{co}}\right), & \text{if } \dfrac{R^{[1]}\left(\mathbf{w}_{\text{co}}\right)}{R_1^{[2]}} \geq \alpha_1, \ \dfrac{R^{[1]}\left(\mathbf{w}_{\text{co}}\right)}{R_2^{[2]}} \geq \alpha_2 \\ \mathcal{S}_{\text{sel}}\left(\mathbf{w}_{i^*}^{\text{MRT}}\right), & \text{otherwise,} \end{cases} \quad (36)$$

where $i^* \in \{1,2\}$ is the index of the selected relay node in the relay selection strategy.

Proof. Based on the results of the previous sections, the expected achievable rates of the relay selection and cooperative transmission strategies and corresponding beamforming vectors are given, respectively, by

$$\overline{R}\left(\mathcal{S}_{\text{sel}}\left(\mathbf{w}_{i^*}^{\text{MRT}}\right)\right) = \min\left\{R_{i^*}^{[1]}\left(\mathbf{w}_{i^*}^{\text{MRT}}\right), \overline{R}_{i^*}^{[2]}\right\}, \quad (37)$$

$$\overline{R}\left(\mathcal{S}_{\text{co}}\left(\mathbf{w}_{\text{co}}\right)\right) = \min\left\{R^{[1]}\left(\mathbf{w}_{\text{co}}\right), \overline{R}^{[2]}\right\}, \quad (38)$$

where $i^* \in \{1,2\}$ is the index of the selected relay node in the relay selection strategy. Since the optimal transmission strategy maximizes the expected achievable rate, the condition that the optimal transmission strategy becomes the cooperative transmission is given by

$$\overline{R}\left(\mathcal{S}_{\text{sel}}\left(\mathbf{w}_{i^*}^{\text{MRT}}\right)\right) \leq \overline{R}\left(\mathcal{S}_{\text{co}}\left(\mathbf{w}_{\text{co}}\right)\right). \quad (39)$$

From (14), since the beamforming vector $\mathbf{w}_i^{\text{MRT}}$ maximizes $R_i^{[1]}(\mathbf{w})$ for all $\|\mathbf{w}\|^2 = 1$, we have

$$\begin{aligned} &\min\left\{R_1^{[1]}\left(\mathbf{w}_1^{\text{MRT}}\right), R_2^{[1]}\left(\mathbf{w}_2^{\text{MRT}}\right)\right\} \geq R^{[1]}\left(\mathbf{w}_{\text{co}}\right) \\ &\Longrightarrow R_{i^*}^{[1]}\left(\mathbf{w}_{i^*}^{\text{MRT}}\right) \geq R^{[1]}\left(\mathbf{w}_{\text{co}}\right), \end{aligned} \quad (40)$$

and, by comparing (7) and (16), we also have

$$\max\left\{\overline{R}_1^{[2]}, \overline{R}_2^{[2]}\right\} \leq \overline{R}^{[2]} \Longrightarrow \overline{R}_{i^*}^{[2]} \leq \overline{R}^{[2]}. \quad (41)$$

Based on the conditions given in (40) and (41), we derive the condition that the optimal transmission strategy becomes the cooperative transmission given in (39).

First, we consider the case that $R_{i^*}^{[1]}(\mathbf{w}_{i^*}^{\text{MRT}}) < \overline{R}_{i^*}^{[2]}$. In this case, based on (37), (38), (40), and (41), we have

$$\begin{aligned} \overline{R}\left(\mathcal{S}_{\text{sel}}\left(\mathbf{w}_{i^*}^{\text{MRT}}\right)\right) &= R_{i^*}^{[1]}\left(\mathbf{w}_{i^*}^{\text{MRT}}\right) \geq R^{[1]}\left(\mathbf{w}_{\text{co}}\right) \\ &= \overline{R}\left(\mathcal{S}_{\text{co}}\left(\mathbf{w}_{\text{co}}\right)\right), \end{aligned} \quad (42)$$

and hence, in this case, the optimal transmission strategy becomes the trust degree-based relay selection. Thus, the necessary condition that the optimal transmission strategy is the cooperative transmission can be obtained by

$$R_{i^*}^{[1]}\left(\mathbf{w}_{i^*}^{\text{MRT}}\right) \geq \overline{R}_{i^*}^{[2]}. \quad (43)$$

When $R_{i^*}^{[1]}(\mathbf{w}_{i^*}^{\text{MRT}}) \geq \overline{R}_{i^*}^{[2]}$, the expected achievable rate of the relay selection is determined by $\overline{R}(\mathcal{S}_{\text{sel}}(\mathbf{w}_{i^*}^{\text{MRT}})) = \overline{R}_{i^*}^{[2]}$. In this case, if $R^{[1]}(\mathbf{w}_{\text{co}}) > \overline{R}^{[2]}$, we have

$$R^{[1]}\left(\mathbf{w}_{\text{co}}\right) > \overline{R}^{[2]} \geq \overline{R}_{i^*}^{[2]} = \overline{R}\left(\mathcal{S}_{\text{sel}}\left(\mathbf{w}_{i^*}^{\text{MRT}}\right)\right), \quad (44)$$

and the optimal transmission strategy is determined by the cooperative transmission.

Otherwise, if $R^{[1]}(\mathbf{w}_{\text{co}}) \leq \overline{R}^{[2]}$, the expected achievable rate of the cooperative transmission is determined by $\overline{R}(\mathcal{S}_{\text{co}}(\mathbf{w}_{\text{co}})) = R^{[1]}(\mathbf{w}_{\text{co}})$, and the condition that the optimal strategy is the cooperative transmission is given by

$$R^{[1]}\left(\mathbf{w}_{\text{co}}\right) \geq \overline{R}_{i^*}^{[2]} = \overline{R}\left(\mathcal{S}_{\text{sel}}\left(\mathbf{w}_{i^*}^{\text{MRT}}\right)\right). \quad (45)$$

Therefore, by combining conditions (40), (43), (44), and (45), we obtain the common condition that the optimal strategy is the cooperative transmission as

$$R_{i^*}^{[1]}\left(\mathbf{w}_{i^*}^{\text{MRT}}\right) \geq R^{[1]}\left(\mathbf{w}_{\text{co}}\right) \geq \overline{R}_{i^*}^{[2]}. \quad (46)$$

From (40) and (46), we have

$$\min\left\{R_1^{[1]}\left(\mathbf{w}_1^{\text{MRT}}\right), R_2^{[1]}\left(\mathbf{w}_2^{\text{MRT}}\right)\right\} \geq \overline{R}_{i^*}^{[2]}, \quad (47)$$

and, from (47), we also have

$$\overline{R}_{i^*}^{[2]} = \max\left\{\overline{R}_1^{[2]}, \overline{R}_2^{[2]}\right\}. \quad (48)$$

Since $R_{i^*}^{[1]}(\mathbf{w}_{i^*}^{\text{MRT}}) \geq R^{[1]}(\mathbf{w}_{\text{co}})$ is always satisfied, from (48), expression (46) can be written by

$$R^{[1]}\left(\mathbf{w}_{\text{co}}\right) \geq \max\left\{\overline{R}_1^{[2]}, \overline{R}_2^{[2]}\right\}. \quad (49)$$

Consequently, using (7) and (49), the condition that the optimal strategy is the cooperative transmission with respect to the trust degrees α_1 and α_2 becomes

$$\begin{aligned} \frac{R^{[1]}\left(\mathbf{w}_{\text{co}}\right)}{R_1^{[2]}} &\geq \alpha_1, \\ \frac{R^{[1]}\left(\mathbf{w}_{\text{co}}\right)}{R_2^{[2]}} &\geq \alpha_2. \end{aligned} \quad (50)$$

Otherwise, the optimal transmission strategy becomes the trust degree-based relay selection. □

Remark 7. In Theorem 6, we first observe that when the channel gains from Tx to the relay nodes are sufficiently larger than those from the relay nodes to Rx such as $R^{[1]}(\mathbf{w}_{\text{co}}) > \max\{R_1^{[2]}, R_2^{[2]}\}$, we obtain $R^{[1]}(\mathbf{w}_{\text{co}})/R_1^{[2]} \geq 1$ and $R^{[1]}(\mathbf{w}_{\text{co}})/R_2^{[2]} \geq 1$. Thus, the cooperative transmission strategy becomes the optimal strategy regardless of trust degrees. In this case, Tx can transmit the data that can be decoded at both of the relay nodes without any rate loss. Thus, by comparing (7) and (16), the cooperative transmission yields a larger expected achievable rate than that of the relay selection for any α_1 and α_2.

Otherwise, the optimal transmission strategy is mainly determined by the trust degrees of relay nodes. When the trust degree of one relay node is relatively larger than that of another relay node, the relay selection strategy becomes the optimal transmission strategy. For example, consider the case in which α_1 is relatively larger than α_2 such as $R^{[1]}(\mathbf{w}_{\text{co}})/R_1^{[2]} < \alpha_1$ and $R^{[1]}(\mathbf{w}_{\text{co}})/R_2^{[2]} \geq \alpha_2$. Then, the expected gain achieved by cooperation of relay node 2 is small due to the low value of α_2. Thus, it is not beneficial that Tx reduces the data rate to be decoded at both relay nodes. Therefore, in this case, the optimal transmission strategy is for Tx to select the relay node that is sufficiently trustworthy and then transmit the data in order to forward it to Rx.

6. Extension to K Relay Nodes

In this section, we extend our proposed strategies for the scenarios with general K ($K > 2$) relay nodes. Let α_k ($k = 1, \ldots, K$) be the trust degree of relay node k. Then, for the relay selection strategy, the expected achievable rate with the selection of relay node k becomes

$$\overline{R}\left(\mathcal{S}_{\text{sel}}\left(\mathbf{w}_k^{\text{MRT}}\right)\right) = \frac{1}{2}\min\left\{R_k^{[1]}\left(\mathbf{w}_k^{\text{MRT}}\right), \overline{R}_k^{[2]}\right\}, \tag{51}$$

where $R_k^{[1]}(\mathbf{w}_k^{\text{MRT}})$ and $\overline{R}_k^{[2]}$ are given in (6) and (7), respectively. In the trust degree-based relay selection strategy, Tx selects the relay node so as to maximize the expected achievable rate. Therefore, for the given trust degrees $[\alpha_1, , \alpha_2, \ldots, \alpha_K]$, the trust degree-based relay selection among K relay nodes is obtained by

$$\mathcal{S}_{\text{sel}}\left(\mathbf{w}_{k^*}^{\text{MRT}}\right) = \underset{k=1,\ldots,K}{\arg\max}\, \overline{R}\left(\mathcal{S}_{\text{sel}}\left(\mathbf{w}_k^{\text{MRT}}\right)\right), \tag{52}$$

and the corresponding expected achievable rate is represented by

$$\overline{R}\left(\mathcal{S}_{\text{sel}}\left(\mathbf{w}_{k^*}^{\text{MRT}}\right)\right) = \max_{k=1,\ldots,K} \overline{R}\left(\mathcal{S}_{\text{sel}}\left(\mathbf{w}_k^{\text{MRT}}\right)\right). \tag{53}$$

For the cooperative transmission strategy, we consider the transmission strategy in which all K relay nodes cooperatively transmit the data to Rx. In this strategy, since K relay nodes must decode the data from Tx, the achievable rate of the cooperative transmission is given by the minimum achievable rate at relay nodes given by

$$\begin{aligned} R^{[1]}(\mathbf{w}) &= \min_{k=1,\ldots,K} R_k^{[1]}(\mathbf{w}) \\ &= \min_{k=1,\ldots,K} \log\left(1 + \rho_T \left|\mathbf{h}_k^\dagger \mathbf{w}\right|^2\right). \end{aligned} \tag{54}$$

Similarly, with the two relay node cases presented in (18), the cooperative beamforming vector for the case of K relay nodes is obtained by

$$\begin{aligned} \mathbf{w}_{\text{co}} &= \underset{\|\mathbf{w}\|^2 \leq 1}{\arg\max}\, R^{[1]}(\mathbf{w}) \\ &= \underset{\|\mathbf{w}\|^2 \leq 1}{\arg\max} \min_{k=1,\ldots,K} \log\left(1 + \rho_T \left|\mathbf{h}_k^\dagger \mathbf{w}\right|^2\right) \\ &= \underset{\|\mathbf{w}\|^2 \leq 1}{\arg\max} \min_{k=1,\ldots,K} \left|\mathbf{h}_k^\dagger \mathbf{w}\right|^2. \end{aligned} \tag{55}$$

Using the equations above, we can find that the beamforming vector design problem becomes a *max-min* problem. Thus, the cooperative beamforming vector $\mathbf{w}_{\text{co}}$ can be obtained by solving the following equivalent problem of a *max-min* problem as follows [22]:

$$\begin{aligned} \mathbf{P1}: \underset{\mathbf{w}}{\text{maximize}} \quad & t \\ \text{subject to} \quad & \mathbf{w}^\dagger \mathbf{h}_k \mathbf{h}_k^\dagger \mathbf{w} \geq t, \\ & \mathbf{w}^\dagger \mathbf{w} \leq 1. \end{aligned} \tag{56}$$

Problem **P1** can be solved by convex optimization with semidefinite relaxation (SDR) [22, 23], and hence the suboptimal cooperative beamforming vector $\mathbf{w}_{\text{co}}$ for the case of K relay nodes can be obtained by solving **P1** [24]. Therefore, for the given trust degrees, the optimal transmission strategy is chosen as the one between the trust degree-based relay selection and cooperative transmission that can obtain higher achievable rates.

7. Numerical Results

In this section, we numerically evaluate the performance of the proposed transmission strategies in terms of the expected achievable rate. As a reference strategy, we compare the proposed strategies to the conventional relay selection strategy $\mathcal{S}_{\text{con}}(\mathbf{w})$, which selects a relay node only based on the channel condition. For the conventional relay selection strategy, the beamforming vector that maximizes the achievable rate is the MRT beamforming vector of selected relay node. Thus, when Tx selects relay node i, the achievable rate of half-duplex DF relaying is given by

$$R_i\left(\mathcal{S}_{\text{con}}\left(\mathbf{w}_i^{\text{MRT}}\right)\right) = \frac{1}{2}\min\left\{R_i^{[1]}\left(\mathbf{w}_i^{\text{MRT}}\right), R_i^{[2]}\right\}, \tag{57}$$

where $R_i^{[2]}$ is given in (8). Therefore, the conventional relay selection strategy maximizes (57) as

$$\mathcal{S}_{\text{con}}\left(\mathbf{w}_{i^*}^{\text{MRT}}\right) = \underset{i=1,2}{\arg\max}\, R_i\left(\mathcal{S}_{\text{con}}\left(\mathbf{w}_i^{\text{MRT}}\right)\right). \tag{58}$$

For the simulation environment, we set the number of antennas at Tx as 2. In addition, we assume that the transmit powers of Tx and the relay nodes are the same as $P_T = P_1 = P_2$, so the transmit SNR is also the same as $\rho_T = \rho_1 = \rho_2$.

In Figures 2 and 3, we plot the expected achievable rates of the proposed transmission strategies according to transmit SNR. The expected achievable rate is obtained by averaging over 10^5 channel realizations. Meanwhile, the trust degrees of relay nodes are given by $\alpha_1 = 0.6$ and $\alpha_2 = 0.3$. Also, the

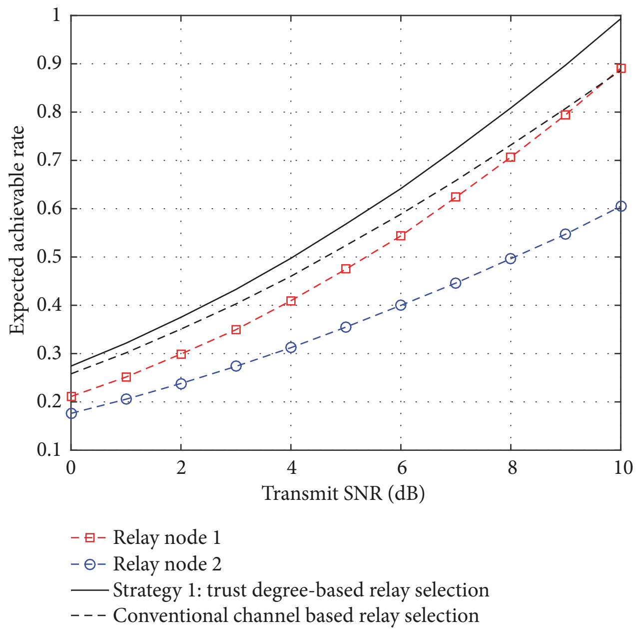

Figure 2: Expected achievable rate versus transmit SNR ($\alpha_1 = 0.6, \alpha_2 = 0.3$).

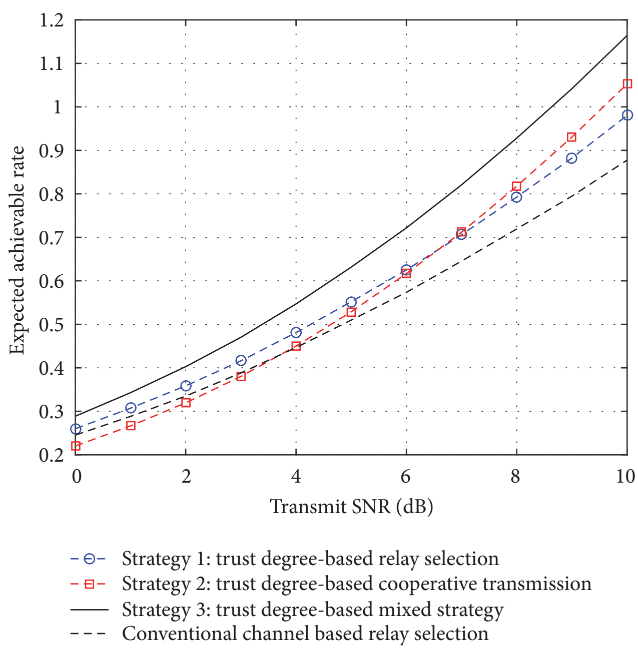

Figure 3: Expected achievable rate versus transmit SNR ($\alpha_1 = 0.6, \alpha_2 = 0.3$).

average channel gains are set as $\sigma_{h_1}^2 = \sigma_{h_2}^2 = \sigma_{g_2}^2 = 0$ dB and $\sigma_{g_1}^2 = -3$ dB, where the relaying channel of relay node 1, which is of a larger trust degree, is worse than that of relay node 2.

In Figure 2, we present the expected achievable rate for the trust degree-based relay selection strategy (Strategy 1). For the purpose of the comparison, we also plot the expected achievable rates of relay node 1, relay node 2, and the conventional channel based relay selection. In Figure 2, we first observe that the expected achievable rate of relay node 1 is larger than that of relay node 2 for the whole SNR region. This can be attributed to the fact that although relay node 1 has a worse relaying channel than relay node 2, relay node 1 helps the transmission of Tx with a higher probability due to the high trust degree. Therefore, in the conventional relay selection, Tx tends to select relay node 2 based on the channel conditions. However, in the trust degree-based relay selection, by considering both trust degree and channel conditions, Tx mainly selects relay node 1, and hence the trust degree-based relay selection increases the expected achievable rate of the conventional relay selection.

In Figure 3, we compare the expected achievable rates of the proposed transmission strategies according to transmit SNR. Comparing the trust degree-based relay selection (Strategy 1) and cooperative transmission (Strategy 2) strategies, the performance of the cooperative transmission is better than that of the relay selection in the high SNR region. However, the trust degree-based relay selection achieves a higher expected achievable rate than the cooperative transmission in the low SNR region. In Theorem 6, $R^{[1]}(\mathbf{w}_{\text{co}})$ generally increases faster than $R_2^{[2]}$ as the transmit SNR increases due to the multiple antennas that are present when the trust degrees are fixed. Therefore, the cooperative transmission achieves a higher expected achievable rate than the relay selection in the high SNR region and vice versa. Since the optimal mixed transmission strategy (Strategy 3) is determined by considering both the trust degree and channel conditions (i.e., transmit SNR), the trust degree-based mixed strategy provides a higher expected achievable rate than the other strategies for all SNR regions.

In Figures 4 and 5, we plot the expected achievable rates of the proposed strategies as a function of relay node 2's trust degree, i.e., α_2. In these figures, we fix the trust degree of relay node 1 as $\alpha_1 = 0.3$, while the trust degree of relay node 2 changes from 0 to 1. The average channel gains are fixed to $\sigma_{h_1}^2 = \sigma_{h_2}^2 = \sigma_{g_2}^2 = 0$ dB and $\sigma_{g_1}^2 = -3$ dB, and the transmit SNR is set to 5 dB.

Figure 4 shows the expected achievable rates of the transmission strategies for the given channel conditions. In this figure, using the average channel gains, we randomly generate the channels and choose one channel realization in order to show the tendency of the expected achievable rates according to α_2. From Figure 4, in the conventional channel based relay selection, since Tx only considers the channel conditions for relay selection, Tx selects relay node 2, which has a larger channel gain regardless of α_2. By contrast, in the trust degree-based relay selection (Strategy 1), Tx selects relay node 1 when the trust degree of relay node 2 is low such as when $\alpha_2 < 0.5059(\alpha_1/\alpha_2 < R_2^{[2]}/R_1^{[2]})$ as shown in Table 1. Furthermore, we can see that the trust degree-based relay selection is chosen as the optimal transmission strategy when α is high such as $\alpha_2 > 0.8204$. Otherwise, the optimal transmission strategy is the trust degree-based cooperative transmission of relay nodes (Strategy 2). This is because the cooperative transmission is the optimal transmission strategy in Theorem 6 as $\alpha_2 < R_{(\mathbf{w}_{\text{co}})}^{[1]}/R_2^{[2]} = 0.8204$, and if the condition is not satisfied, the relay selection strategy is the

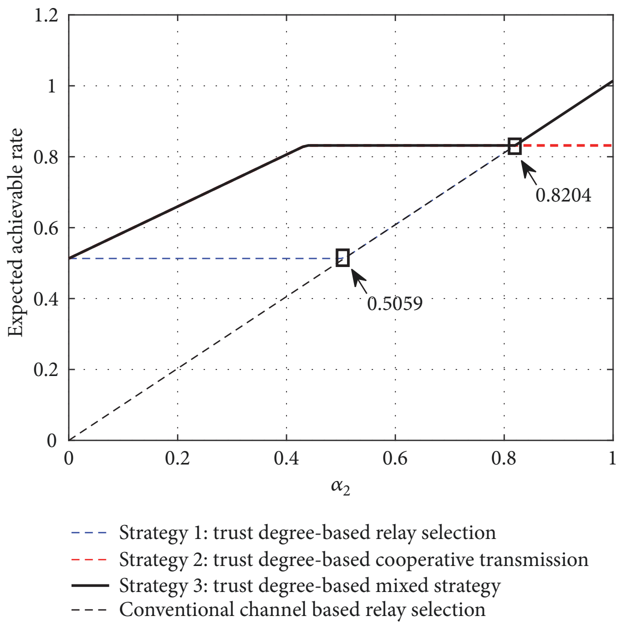

FIGURE 4: Expected achievable rate versus α_2 for the given channel conditions ($\alpha_1 = 0.3$, SNR = 5 dB).

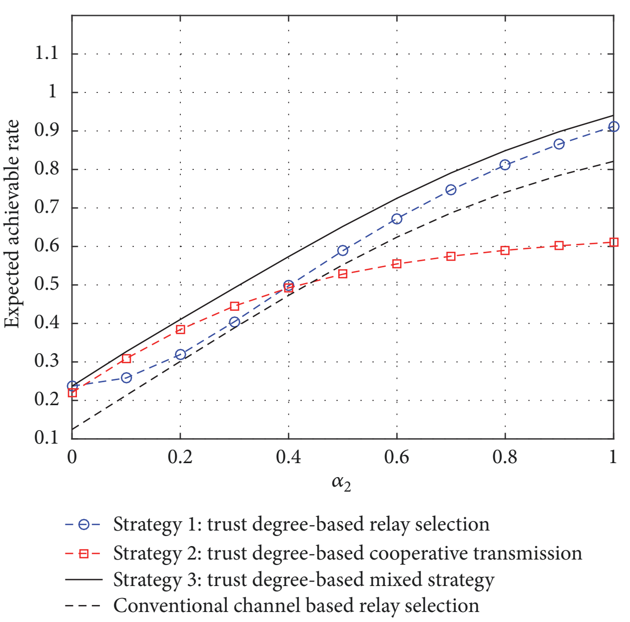

FIGURE 5: Expected achievable rate versus α_2 ($\alpha_1 = 0.3$, SNR = 5 dB).

optimal transmission strategy that maximizes the expected achievable rate.

In Figure 5, the expected achievable rates of the transmission strategies are plotted with respect to α_2. In this figure, the expected achievable rate is obtained by averaging over 10^5 channel realizations. From Figure 5, we can observe a similar result as in Figure 4. For the region in which α_2 is small, the trust degree-based cooperative transmission (Strategy 2) provides better performance than the trust degree-based relay selection (Strategy 1) since the condition in Theorem 6

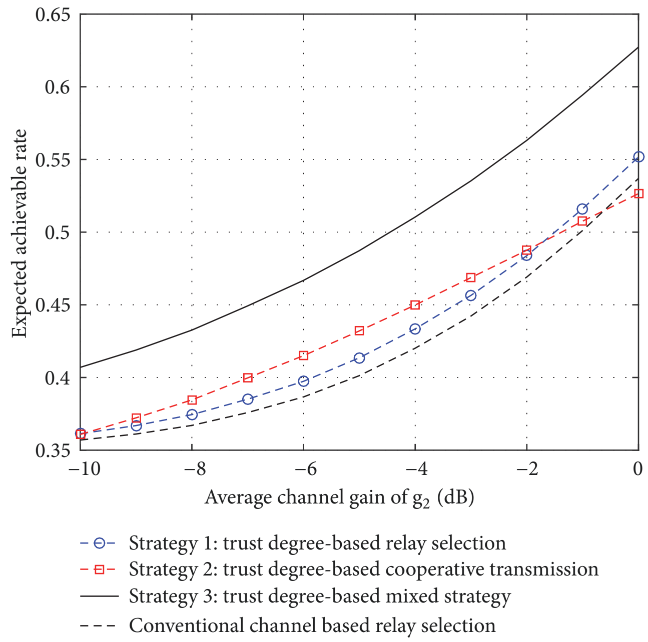

FIGURE 6: Expected achievable rate versus $\sigma_{g_2}^2$ ($\alpha_1 = 0.6, \alpha_2 = 0.4$, and SNR = 5 dB).

is satisfied. On the other hand, when α_2 is sufficiently large, it is shown that Tx selects a single relay node, which has good channel conditions and a high trust degree as the optimal transmission strategy. In addition, when the values of α_1 and α_2 are similar, such as when $\alpha_2 \approx 0.3$, the performance gap between the trust degree-based relay selection and channel condition based relay selection strategies becomes marginal. In this case, the trust degrees of relay nodes have a similar effect on the achievable rate, and the effect of the channel conditions is dominant on the achievable rate.

Figure 6 shows the performance of the transmission strategies with respect to the average channel gain of relay node 2's relaying channel, i.e., $\sigma_{g_2}^2$. The average channel gains of $\mathbf{h}_1$, $\mathbf{h}_2$, and g_1 are set as $\sigma_{h_1}^2 = \sigma_{h_2}^2, \sigma_{g_1}^2 = -3$ dB, and the value of $\sigma_{g_2}^2$ varies from -10 dB to 0 dB. The trust degrees of relay nodes and the transmit SNR are set as $\alpha_1 = 0.6$, $\alpha_2 = 0.4$, and $\rho_T = 5$ dB, respectively. In Figure 6, when the average channel gain of g_2 is small, the trust degree-based cooperative transmission (Strategy 2) is more beneficial than the trust degree-based relay selection strategy (Strategy 1) due to the condition in Theorem 6, and the performance gap becomes large when the relaying channel gains of relay nodes are similar, such as when $\sigma_{g_2}^2 \approx -5$ dB. By contrast, if the average channel gain of g_2 is much larger than that of g_1, the performance gain achieved by cooperative transmission becomes marginal on the achievable rate, and hence the relay selection strategy is more efficient than the cooperative transmission.

8. Conclusion

In this paper, we proposed efficient transmission strategies considering the trust degrees of relay nodes in MISO cooperative communication systems with two relay nodes. We first proposed the trust degree-based relay selection and provided the selection strategy that maximizes the expected achievable rate with respect to the trust degrees. We then proposed the cooperative transmission of relays and designed the closed form beamforming vector for cooperative transmission, which is a linear combination of channel vectors. Furthermore, based on the proposed strategies, we derived the optimal mixed transmission strategy that maximizes the expected achievable rate according to trust degrees and extended the proposed strategies to the cooperative communication systems with K relays. Compared to the conventional strategy that only considers the channel conditions, we numerically showed that the proposed transmission strategies that consider both channel conditions and trust degree of relay node can increase the expected achievable rate.

Data Availability

The simulation data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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