The 18th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC'07)

COOPERATIVE TRANSMISSION SCHEMES FOR DECODE-AND-FORWARD RELAYING

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ABSTRACT

We consider a low mobility cellular relaying system downlink where two mobile users are served by two neighboring decode-and-forward relays concurrently using the same frequency channel. We propose two cooperative relaying transmission schemes where each relay can choose proper precoding vectors based on its *local* channel knowledge to transmit data in the second hop. Each user can receive its own data without interference, which simplifies the user receiver design. We show that the diversity of each user's received data signal can be improved by receiving data from multiple relays. In addition, higher array gain can be achieved by the first scheme at the cost of higher synchronization accuracy requirements. Furthermore, we show that the two transmission schemes achieve higher transmission rate than serving different users in separate channels.

I. INTRODUCTION

In recent years, multihop communication has become an active and vital area of research in wireless communication. In a cellular network, relaying schemes provide promising technologies to transmit at higher data rate to destinations farther away [1]. In order to increase the coverage area, multiple relays need to be placed in the cellular system. As a result, some users will inevitably be in the overlap of the coverage regions of neighboring relays. Thus it is interesting to consider how to transmit data to multiple users using multiple relays cooperatively.

The concept of *cooperative transmission* can be found in e.g. [2], where the authors consider an uplink scenario where two users in a cellular network share part of their data, and that part is transmitted coherently using the same codebook. By doing so, the authors show that the capacity region is increased. In [3], the authors propose a *multiuser zero-forcing relaying scheme* in a network with multiple source and destination nodes. The communication between those source-destination pairs is facilitated by multiple amplify-and-forward (AF) relays. Each node is equipped with a single antenna. The authors propose a novel relay gain allocation scheme to orthogonalize the channel between those source-destination pairs. Multiuser interference is canceled by this scheme.

We consider a low mobility cellular relaying system downlink with multiple decode-and-forward (DF) relays. DF relays do not cause noise amplification. Thus they may be more preferable in cellular systems. In a cellular system, the relays are usually intentionally placed where there is good wireless connection to the base station. So the base station to relay station (BS-RS) channel is usually very good and should not be

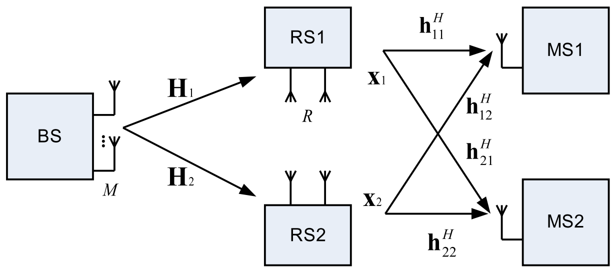

Figure 1: System Model

the bottleneck for multihop transmissions. Since the system is in low mobility, we assume the relays have channel knowledge about the second hop. But we assume each relay only has its *local* channel knowledge. That is, each relay only knows the channel from its own antennas to the mobile stations (MS). Such channel knowledge can be achieved by the uplink transmission in a TDD (Time division duplex) communication system between the relays and mobiles or by the channel feedback from the users. There is no need to exchange data or channel knowledge between different relays. By using their local channel knowledge, the relays can choose proper precoding vectors and cancel the co-channel interference in the second hop transmission. So the complexity is moved to the transmitter side (i.e., relays), and the MS receivers are kept simple. In addition, the transmit maximal ratio combining [4] or space-time coding schemes [5] can be combined with interference cancelation to provide additional array gain and diversity gain to the received MS data signals. In order to transmit to the users *cooperatively*, the relays have to achieve a certain level of synchronization when they transmit. We will show that by transmitting to the users concurrently using the same frequency channel, we achieve higher multiplexing gain compared to transmitting to different users using different channels. By using multiple relays to transmit *cooperatively*, the diversity of the received signals at each user is also improved.

The paper is organized as follows: The system model is discussed in Section II. The details of the proposed *cooperative maximum ratio combining (MRC) transmission scheme* will be discussed in Section III, and the *cooperative Alamouti transmission scheme* will be discussed in Section IV. Comprehensive simulation results are presented in Section V, where we show the transmission rate improvement achieved by the proposed schemes. The impact of noisy channel knowledge is also investigated. After that, the conclusions will be drawn in Section VI.

II. System Model

The system model is depicted in Fig. 1. We consider a low mobility cellular relaying system downlink with one BS, two DF relays and two mobile users. We assume there is no direct connection between BS and MS due to the distance between them. The relays are placed where there is good wireless link to the BS. As a starting point, we only consider each MS just has one antenna in this paper. We denote the number of antennas at each BS, RS and MS as $M/R/1$, respectively. We assume $M \geq R > 1$. The channel between BS and relay i is denoted as $\mathbf{H}_i \in \mathbb{C}^{R\times M}$, where $i = 1, 2$. The second hop channel between relay i and mobile station j is denoted as $\mathbf{h}_{ji} \in \mathbb{C}^R$, where $(i, j) \in \{1, 2\}^2$. The channels between the nodes are i.i.d. block fading. We also assume flat fading channels, which corresponds to one subcarrier in OFDM modulation. Each relay just has its *local* channel knowledge about the second hop. That is, RS_1 just has the channel knowledge of $\mathbf{h}_{11}^H$ and $\mathbf{h}_{21}^H$, and RS_2 just knows the channel $\mathbf{h}_{12}^H$ and $\mathbf{h}_{22}^H$. We call $\mathbf{h}_{11}^H$ and $\mathbf{h}_{22}^H$ *direct-link channels*, and call $\mathbf{h}_{12}^H$ and $\mathbf{h}_{21}^H$ *cross-link channels*. We denote the power constraint at BS and each RS as P_{BS} and P_{RS}, respectively. We assume circularly symmetric zero mean complex Gaussian noise at the RS and MS receivers, and their variances are denoted as σ^2_{RS} and σ^2_{MS}, respectively.

Since current relays cannot transmit and receive signals using the same channel, we just consider half-duplex relays. The BS needs at least two phases to transmit the data to the mobile users. In the first phase, the data is transmitted from the BS to the two relays. This is a *multicast* or *broadcast* scenario depending on whether the two relays decode the same information. In the second phase, the two relays communicate with the two users MS_1 and MS_2 simultaneously in the same frequency channel. The two relays utilize their channel knowledge to do interference pre-cancelation at the transmitters so that each MS just receives its own data. This will be discussed in detail in the following sections.

III. Cooperative Maximum Ratio Combining Transmission Scheme

In a cellular scenario, the second hop channel, i.e. the channel between the RS and MS, is usually the bottleneck of the relaying system. The *cooperative maximum ratio combining (MRC) transmission scheme* utilizes the cross-link channel to improve the diversity gain. It also aligns the phase of the received signal at each user so that additional array gain is achieved.

We denote the data symbols to be transmitted to MS_1 and MS_2 as s_1 and s_2, respectively. In the first phase, the BS transmits a data symbol vector $\mathbf{s} \in \mathbb{C}^M$ to both relays. This symbol vector $\mathbf{s}$ contains both s_1 and s_2 . This is a *multicast* scenario because the two relays receive the same information. Since we require both relays to perfectly decode the data signals from the BS, the maximum transmission rate of the first hop can be expressed as

$$\begin{aligned} \text{R}_1 = \max_{\mathbf{\Gamma}} \min\Big\{ & \log_2 \det \left(\mathbf{I}_R + \frac{1}{\sigma^2_{\text{RS}}} \mathbf{H}_1 \mathbf{\Gamma} \mathbf{H}_1^H \right), \\ & \log_2 \det \left(\mathbf{I}_R + \frac{1}{\sigma^2_{\text{RS}}} \mathbf{H}_2 \mathbf{\Gamma} \mathbf{H}_2^H \right) \Big\}, \end{aligned} \quad (1)$$

where $\text{tr}(\mathbf{\Gamma}) = \text{tr}(\mathbf{s}\mathbf{s}^H) = P_{\text{BS}}$.

After the relays decode the data from the BS, the signal vectors transmitted from RS_1 and RS_2 in the second phase can be expressed as

$$\mathbf{x}_1 = s_1 \mathbf{w}_1 + s_2 \mathbf{w}_2, \quad (2)$$
$$\mathbf{x}_2 = s_1 \mathbf{w}_3 + s_2 \mathbf{w}_4. \quad (3)$$

Here $\mathbf{w}_k \in \mathbb{C}^R$ $(k = 1, \ldots, 4)$ are the precoding vectors. We require $\text{tr}(\mathbf{w}_k \mathbf{w}_k^H) = 1$ so that the transmit power constraint is satisfied. Furthermore, we require the precoding vectors satisfy the following conditions

$$\mathbf{h}_{21}^H \cdot \mathbf{w}_1 = 0, \quad \mathbf{h}_{11}^H \cdot \mathbf{w}_2 = 0, \quad (4)$$
$$\mathbf{h}_{22}^H \cdot \mathbf{w}_3 = 0, \quad \mathbf{h}_{12}^H \cdot \mathbf{w}_4 = 0. \quad (5)$$

That is, the precoding vectors lie in the null space of the corresponding channels. Such precoding vectors always exist because we have more antennas at each RS than each MS. The null space dimension of $\mathbf{h}_{ij}^H$ is larger than 0 for i.i.d. Gaussian channels $\forall (i, j) \in \{1, 2\}^2$. By using such precoding vectors, the co-channel interference is canceled and each data symbol is only transmitted to its intended user.

Based on (2), (3), (4) and (5), the received signal at MS_1 and MS_2 can be expressed as

$$y_1 = (\mathbf{h}_{11}^H \mathbf{w}_1 + \mathbf{h}_{12}^H \mathbf{w}_3) s_1 + n_1, \quad (6)$$
$$y_2 = (\mathbf{h}_{12}^H \mathbf{w}_2 + \mathbf{h}_{22}^H \mathbf{w}_4) s_2 + n_2. \quad (7)$$

where n_1 and n_2 are the Gaussian noise at MS_1 and MS_2, respectively. In order to satisfy the power constraint, we have $\text{E}(s_1 s_1^* + s_2 s_2^*) = P_{\text{RS}}$. Here s_1 and s_2 are the data signals transmitted from the relays.

Since we assume each mobile user just has one receive antenna, each $\mathbf{h}_{ij}^H \mathbf{w}_k$ $((i, j) \in \{1, 2\}^2; k = 1, \ldots, 4)$ in (6) and (7) is a complex number. For any precoding vector $\mathbf{w}_k$ satisfying (2)-(5), $\mathbf{w}_k e^{j\phi}$ is also a suitable precoding vector. Thus we can choose the precoding vectors such that the terms $\mathbf{h}_{ij}^H \mathbf{w}_k$ in (6) and (7) all have zero phases. That is

$$\angle(\mathbf{h}_{11}^H \mathbf{w}_1) = \angle(\mathbf{h}_{12}^H \mathbf{w}_3) = \angle(\mathbf{h}_{12}^H \mathbf{w}_2) = \angle(\mathbf{h}_{22}^H \mathbf{w}_4) = 0 \quad (8)$$

Such precoding vectors can be easily calculated. For example, if $\mathbf{w}_1^0$ is found to lie in the null space of $\mathbf{h}_{21}^H$, we can calculate the final precoding vector at RS_1 as

$$\mathbf{w}_1 = \mathbf{w}_1^0 \cdot \frac{\left(\mathbf{h}_{11}^H \mathbf{w}_1^0\right)^*}{|\mathbf{h}_{11}^H \mathbf{w}_1^0|}. \quad (9)$$

It can be shown that the precoding vector obtained by (9) is unique and is not dependent on the choice of $\mathbf{w}_1^0$. By choosing the precoding vector $\mathbf{w}_1$ as in (9), the equivalent channel between RS_1 and MS_1 is

$$\mathbf{h}_{11}^H\mathbf{w}_1 = \mathbf{h}_{11}^H\mathbf{w}_1^0 \cdot \frac{\left(\mathbf{h}_{11}^H\mathbf{w}_1^0\right)^*}{|\mathbf{h}_{11}^H\mathbf{w}_1^0|} = |\mathbf{h}_{11}^H\mathbf{w}_1^0| = |\mathbf{h}_{11}^H\mathbf{w}_1|. \quad (10)$$

From the last equation, it follows that $\mathbf{h}_{11}^H\mathbf{w}_1$ is a positive real number. Other precoding vectors $\mathbf{w}_k$ ($k = 2,3,4$) can be calculated in a similar way. As a result, the SNRs at MS_1 and MS_2 can be expressed as

$$\mathrm{SNR}_{1,\mathrm{MRC}} = \frac{\left(|\mathbf{h}_{11}^H\mathbf{w}_1| + |\mathbf{h}_{12}^H\mathbf{w}_3|\right)^2 \cdot \mathrm{E}(s_1 s_1^*)}{\sigma_{\mathrm{MS}}^2}, \quad (11)$$

$$\mathrm{SNR}_{2,\mathrm{MRC}} = \frac{\left(|\mathbf{h}_{21}^H\mathbf{w}_2| + |\mathbf{h}_{22}^H\mathbf{w}_4|\right)^2 \cdot \mathrm{E}(s_2 s_2^*)}{\sigma_{\mathrm{MS}}^2}. \quad (12)$$

The maximum transmission rate of the second hop is

$$\mathrm{R}_{2,\mathrm{MRC}} = \log_2(1+\mathrm{SNR}_{1,\mathrm{MRC}}) + \log_2(1+\mathrm{SNR}_{2,\mathrm{MRC}}). \quad (13)$$

Due to two hop transmission, the overall transmission rate of the scheme is

$$\mathrm{R}_{\mathrm{MRC}} = \frac{1}{2} \cdot \min(\mathrm{R}_1, \mathrm{R}_{2,\mathrm{MRC}}). \quad (14)$$

In order to analyze the diversity of the received signal, we consider a Rayleigh fading channel $\mathbf{h}_{ij} \sim \mathcal{CN}(0, \sigma_{ij}^2\mathbf{I}_R)$ for $(i,j) \in \{1,2\}^2$, where σ_{ij}^2 is the channel variance. Since $\mathrm{tr}(\mathbf{w}_k\mathbf{w}_k^H) = 1$ for $k = 1,\ldots,4$, $\mathbf{h}_{ij}^H\mathbf{w}_k$ is a linear combination of complex Gaussian random variables. Because of the isotropic property of complex Gaussian random vectors [6], the resultant $\mathbf{h}_{ij}^H\mathbf{w}_k$ is a Gaussian random variable with variance σ_{ij}^2. By examining (11) and (12), we can easily see that cooperative MRC transmission scheme provides second order diversity if the cross-link and direct-link are equally strong. Because the received signals from different relays have the same phase, they add up coherently at the receivers. So we get additional array gain. In order to align the phases of the received signals, we need phase synchronization between the relays, i.e., the two relays require a global phase reference. The cooperative MRC scheme serves two users at the same time and has full rate transmission for each receiver. This is achieved without using additional resources or exchanging channel knowledge and data between different relays.

IV. Cooperative Alamouti Transmission Scheme

Like the cooperative MRC transmission scheme, the cooperative Alamouti transmission scheme also uses the second hop channel knowledge to cancel co-channel interference to the mobile users from the relay side. In addition, space-time coding (Alamouti scheme) is used to provide diversity to the mobile users. Thus we just need symbol level synchronization between the relays, which is easier to achieve.

We denote the data symbols to be transmitted from BS to MS_1 as $s_1^{(1)}$ and $s_1^{(2)}$, and the data symbols to be transmitted to MS_2 as $s_2^{(1)}$ and $s_2^{(2)}$, respectively. In the first transmission phase, the BS transmits all the data to both relays in two time slots. The rate expression of the first hop in each time slot is the same as (1).

After the two relays perfectly decode the four symbols, they retransmit the data to the two mobile users in the second phase. The second phase is composed of two time slots. In the first time slot, RS_1 and RS_2 transmit the following signal

$$\mathbf{x}_1^{(1)} = s_1^{(1)}\mathbf{w}_1 + s_2^{(1)}\mathbf{w}_2, \quad (15)$$

$$\mathbf{x}_2^{(1)} = s_1^{(2)}\mathbf{w}_3 + s_2^{(2)}\mathbf{w}_4, \quad (16)$$

where $\mathbf{w}_k \in \mathbb{C}^R$ ($k = 1,\ldots,4$) is the precoding vector. They satisfy (4), (5) and $\mathrm{tr}(\mathbf{w}_k\mathbf{w}_k^H) = 1$. In the second time slot, the signals transmitted at RS_1 and RS_2 are

$$\mathbf{x}_1^{(2)} = \left(-s_1^{(2)}\right)^*\mathbf{w}_1 + \left(-s_2^{(2)}\right)^*\mathbf{w}_2, \quad (17)$$

$$\mathbf{x}_2^{(2)} = \left(s_1^{(1)}\right)^*\mathbf{w}_3 + \left(s_2^{(1)}\right)^*\mathbf{w}_4, \quad (18)$$

Since the multiuser interference is canceled by the precoding vectors, the received signal at MS_1 and MS_2 can be expressed as

$$\mathbf{y}_1 = \begin{bmatrix} \mathbf{h}_{11}^H\mathbf{w}_1 & \mathbf{h}_{12}^H\mathbf{w}_3 \\ (\mathbf{h}_{12}^H\mathbf{w}_3)^* & -(\mathbf{h}_{11}^H\mathbf{w}_1)^* \end{bmatrix}\mathbf{s}_1 + \mathbf{n}_1, \quad (19)$$

$$\mathbf{y}_2 = \begin{bmatrix} \mathbf{h}_{21}^H\mathbf{w}_2 & \mathbf{h}_{22}^H\mathbf{w}_4 \\ (\mathbf{h}_{22}^H\mathbf{w}_4)^* & -(\mathbf{h}_{21}^H\mathbf{w}_2)^* \end{bmatrix}\mathbf{s}_2 + \mathbf{n}_2, \quad (20)$$

where $\mathbf{y}_i = \left[y_i^{(1)}, (y_i^{(2)})^*\right]^T$, $i = 1,2$ is the received signal vectors at MS_i, $\mathbf{s}_i = \left[s_i^{(1)}, s_i^{(2)}\right]^T$ is the transmitted signal vector, and $\mathbf{n}_i = \left[n_i^{(1)}, (n_i^{(2)})^*\right]^T$ is the noise vector at MS_i.

The received SNR for each symbol at MS_1 and MS_2 can be derived as the traditional Alamouti scheme [7]

$$\mathrm{SNR}_{1,\mathrm{A}} = \frac{\left(|\mathbf{h}_{11}^H\mathbf{w}_1|^2 + |\mathbf{h}_{12}^H\mathbf{w}_3|^2\right) \cdot \mathrm{E}\left(s_1^{(1)}(s_1^{(1)})^*\right)}{\sigma_{\mathrm{MS}}^2}, \quad (21)$$

$$\mathrm{SNR}_{2,\mathrm{A}} = \frac{\left(|\mathbf{h}_{21}^H\mathbf{w}_2|^2 + |\mathbf{h}_{22}^H\mathbf{w}_4|^2\right) \cdot \mathrm{E}\left(s_2^{(1)}(s_2^{(1)})^*\right)}{\sigma_{\mathrm{MS}}^2}, \quad (22)$$

where $\mathrm{E}\left(s_1^{(1)}(s_1^{(1)})^* + s_2^{(1)}(s_2^{(1)})^*\right) = P_{RS}$. Here we assumed $s_i^{(1)}$ and $s_i^{(2)}$ have equal power, where $i = 1,2$. The maximum transmission rate for the second hop in each time slot is

$$\mathrm{R}_{2,\mathrm{A}} = \log_2(1+\mathrm{SNR}_{1,\mathrm{A}}) + \log_2(1+\mathrm{SNR}_{2,\mathrm{A}}). \quad (23)$$

Due to two hop transmissions, the overall rate of the system can be calculated as

$$\mathrm{R}_{\mathrm{A}} = \frac{1}{2} \cdot \min(\mathrm{R}_1, \mathrm{R}_{2,\mathrm{A}}). \quad (24)$$

If we assume Rayleigh fading for the second hop channels, $\mathbf{h}_{ij}^H\mathbf{w}_k$ ($(i,j) = \{1,2\}^2; k = 1,\ldots,4$) is a Gaussian random variable. (21) and (22) shows that the received signal has second order diversity but has no array gain. In this scheme, we only need symbol synchronization between the relays, which is an advantage compared to the cooperative MRC scheme. The cooperative Alamouti transmission scheme also achieves full rate transmission without using additional bandwidth or exchange channel knowledge between the relays.

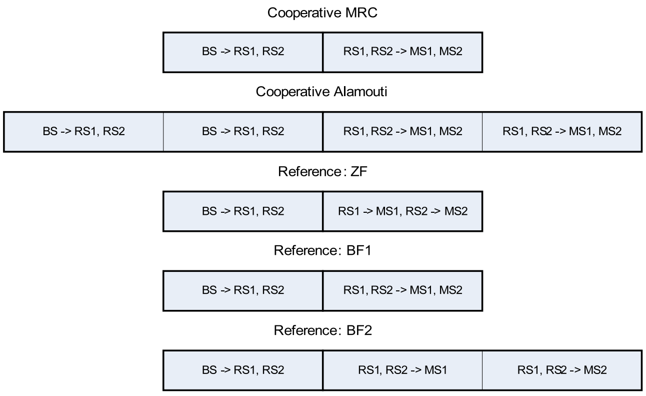

Figure 2: Timing of different schemes

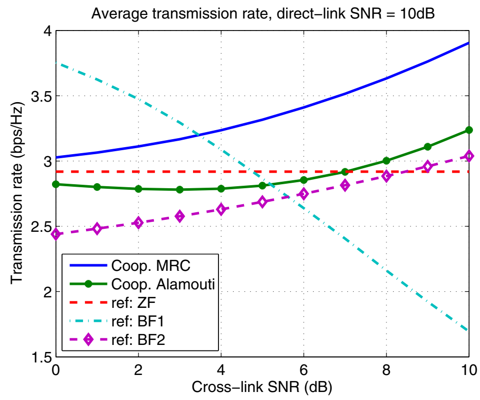

Figure 3: Average transmission rate, the 1st hop SNR = 20dB, the 2nd hop direct-link SNR = 10dB

V. Simulation Results

A. Reference Scenarios and Simulation Setup

In order to verify the rate improvement provided by the proposed schemes, we consider the following reference scenarios:

1) Zero forcing (ZF)

In the second hop transmission, RS_1 and RS_2 just transmit the data of MS_1 and MS_2, respectively. The relays use precoding vectors to cancel the interference to the cross-link. That is, we choose precoding vectors $\mathbf{w}_1$ and $\mathbf{w}_4$ according to (4) and (5). The signal transmitted from the relays in the second hop can be expressed as

$$\mathbf{x}_1 = s_1 \mathbf{w}_1, \quad \mathbf{x}_2 = s_2 \mathbf{w}_4, \tag{25}$$

where $\mathrm{E}(s_1 s_1^*) = \mathrm{E}(s_2 s_2^*) = P_{\mathrm{RS}}$.

2) Beamforming case 1 (BF1)

In this reference scenario, RS_1 and RS_2 just transmit data to MS_1 and MS_2, respectively. Beamforming vectors are applied at the transmitter side. The beamforming vectors at RS_1 and RS_2 are chosen as

$$\mathbf{g}_1 = \frac{\mathbf{h}_{11}}{\|\mathbf{h}_{11}\|_F}, \quad \mathbf{g}_2 = \frac{\mathbf{h}_{22}}{\|\mathbf{h}_{22}\|_F}. \tag{26}$$

The signals transmitted from RS_1 and RS_2 are

$$\mathbf{x}_1 = s_1 \mathbf{g}_1, \quad \mathbf{x}_2 = s_2 \mathbf{g}_2, \tag{27}$$

where $\mathrm{E}(s_1 s_1^*) = \mathrm{E}(s_2 s_2^*) = P_{\mathrm{RS}}$. Each user receives both its data and interferences.

3) Beamforming case 2 (BF2)

In this reference scenario, both relays use two time slots to transmit to the mobile users. In the first time slot, RS_1 and RS_2 just transmit data to MS_1, while they just transmit data to MS_2 in the second time slot. In each time slot, the two relays do beamforming to transmit to the destination. In this case, there is no co-channel interference at the MS receivers because time orthogonal channels are used.

Simulations are carried out to compare the performance of the proposed schemes with the above mentioned reference scenarios. In our simulations, the first and second hop channels are i.i.d. Rayleigh fading channels. We assume $\mathbf{h}_{ij} \sim \mathcal{CN}(0, \sigma_{ij}^2 \mathbf{I}_R)$ for $(i,j) = \{1,2\}^2$, where σ_{ij}^2 is the channel variance. The direct-link and cross-link SNRs are defined as

$$\mathrm{SNR}_{\mathrm{dct}} = \frac{P_{\mathrm{RS}} \sigma_{ii}^2}{\sigma_{\mathrm{MS}}^2}, \quad \mathrm{SNR}_{\mathrm{crs}} = \frac{P_{\mathrm{RS}} \sigma_{ij}^2}{\sigma_{\mathrm{MS}}^2}, \tag{28}$$

respectively, where $\{i,j\} = \{1,2\}^2$ and $i \neq j$.

The simulation setup is as follows:

- The number of antennas at BS, RS and MS is 4/2/1, respectively;
- The received SNR at the relays of the first hop is fixed at 20dB;
- The transmission schemes are summarized in Fig. 2. Each time slot takes unit time. In order to make fair comparison between different schemes, the transmission rate is normalized to the channel uses each scheme takes.
- Different power allocation for different MS data is applied at each relay. It is based on the local channel knowledge of the second hop.

B. Impact of Channel Strength

The average transmission rates of the proposed schemes compared to the reference scenarios are shown in Fig. 3. In the second hop, the direct-link (RS_i to MS_i) SNR is fixed at 10dB, while the cross-link SNR varies from 0 to 10dB. Fig. 3 shows that when the cross-link is very weak, it is better to do transmit beamforming at each relay transmitter irrespective of the existence of other relays. The interference caused at the receiver remains very small. In such a case, trying to cancel the cross-link interference is not necessary and it wastes one spatial degree of freedom at the transmitter. But as the cross-link becomes stronger, the "crosstalk" interference received at the receiver leads to severe degradation in the performance if we just do transmit beamforming without interference cancelation.

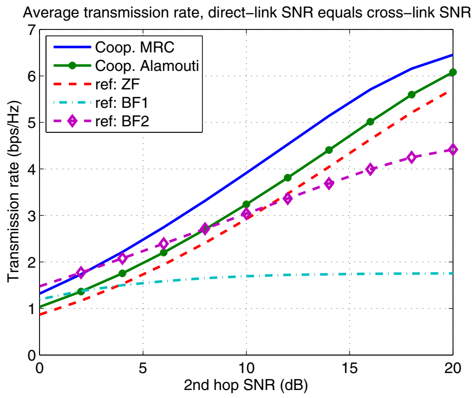

Figure 4: Average transmission rate. The 1st hop SNR = 20dB. The 2nd hop direct-link SNR equals the cross-link SNR. They vary from 0dB to 20dB.

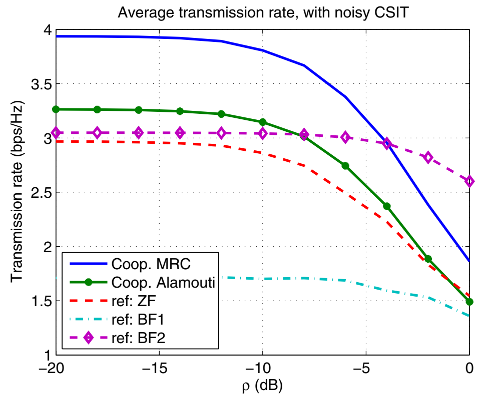

Figure 5: Average transmission rate with noisy channel state information (CSIT) at relays. The 1st hop SNR = 20dB. The 2nd hop direct-link SNR and the cross-link SNR both equal 10dB.

Our proposed cooperative MRC scheme outperforms the other schemes when the cross-link SNR is higher than 4dB, while the cooperative Alamouti scheme has higher transmission rate than the reference scenarios when the cross-link SNR is higher than 7dB. That means when the cross-link and direct-link are approximately equally strong, our new schemes are preferable.

Fig. 4 shows the average transmission rate when the direct-link and cross-link are equally strong. The average transmission rates of our proposed schemes and the zero forcing reference scenario scale the same way. This is because the three schemes have the same multiplexing gain. That is, the relays transmit to both users using the same time and frequency channel. In the BF2 reference scenario, the relays serve each user using different channels, thus the multiplexing gain is lost. This can be seen from the smaller slope in the average transmit rate of BF2 reference scenario. But since we use two relays to serve one mobile user each at a time, the received signal has higher diversity gain and array gain. That is why the BF2 reference scenario has a higher transmission rate in the low SNR regime.

C. *Impact of Noisy Channel Knowledge*

Our schemes require channel knowledge about the second hop to cancel interference. The impact of imperfect channel knowledge is worth investigating. In this subsection, we assume the relays have noisy channel knowledge. That is, the channel knowledge at relays is

$$\tilde{\mathbf{h}}_{ij} = \mathbf{h}_{ij}^H + \hat{\mathbf{h}}_{ij}, \quad i,j = 1,2. \tag{29}$$

$\hat{\mathbf{h}}_{ij} \sim \mathcal{CN}(0, \hat{\sigma}_{ij}^2 \mathbf{I}_R)$, and each entry of $\hat{\mathbf{h}}_{ij}$ is modeled as i.i.d. circularly symmetric zero mean complex Gaussian random variable. We define $\rho = \hat{\sigma}_{ij}^2/\sigma_{ij}^2$. The simulation results are shown in Fig. 5. All the schemes involving interference cancelation are sensitive to noisy channel. The BF2 reference scenario is robust to noisy channel knowledge. This is because the relays serve each user using different channels in such a reference scenario. Even when the channel knowledge is imperfect, the relays do not generate interference to the other users.

VI. Conclusions

We propose two cooperative relaying schemes using DF relays. Both schemes do not require the relays to exchange transmission data or channel knowledge. The received signal at each user is interference free. The cooperative MRC scheme provides the best performance, but it also requires the highest level of synchronization (phase synchronization). The cooperative Alamouti scheme is preferable if phase synchronization is not available. Both schemes outperform the reference scenarios when the cross-link is reasonably strong.

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