Three-Way Massive MIMO Relaying with Successive Cancelation Decoding

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Abstract. In this paper, we propose a novel transmission scheme for a three-way massive multiple-input multiple-output (MIMO) relay network where three users exchange their data with the help of a decode-and-forward relay station equipped with a very large antenna array. Our proposed scheme needs only two time-slots for the information exchange. More precisely, the three users first send their symbols to the relay. Then, the relay uses the maximum-ratio combining technique to decode all transmitted symbols and simultaneously transmits these symbols to all three users. Each user applies successive cancelation decoding to decode symbols transmitted from other users. We study the sum spectral efficiency of our proposed transmission protocol. We show that the sum spectral efficiency of our proposed scheme increases noticeably compared to the one of the conventional scheme where three time-slots are required to exchange data among the three users, without increasing the system complexity.

Keywords: Decode-and-forward · Maximum-ratio combining
Multi-way relay massive MIMO · Successive cancelation decoding

1 Introduction

Over the past decade, multi-way relaying networks have received a lot of research interest [1–3]. In multi-way relaying networks, multiple users located in different areas in the networks exchange their data with the help of a relay. The relay can be equipped with single or multiple antennas and can use different processing such as amplify-and-forward (AF) or decode-and-forward (DF). It was shown in [1] that multi-way relaying systems can boost the spectral efficiency and energy efficiency of the system, as well as, the robustness against the channel variations in different propagation environments. Furthermore, in [2,3], the authors illustrated that multi-way relaying networks offer higher communication reliability than one-way or two-way relaying systems do.

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In parallel, there has also been a great deal of interest in massive MIMO [4–6] since it can serve at the same time many users with good service, and with very low power consumption. In massive MIMO, the base station (BS) is equipped with hundreds or thousands antennas using simple linear processing to serve simultaneously tens or hundreds users in the downlink and the uplink. Owing to the favorable propagation property of massive MIMO (the channel vectors between the BS and the users are (nearly) pairwisely orthogonal when the number of antennas is large), the uncorrelated noise and inter-user interference disappear with simple linear processing such as maximum-ratio and zero-forcing processing. This makes massive MIMO feasible for practical implementation [7]. More importantly, by leveraging time division duplex (TDD) mode, massive MIMO is scalable to any desired degrees of freedom with respect to the number of antennas at the BS [2]. For all above reasons, massive MIMO is a very strong candidate for the fifth-generation (5G) of wireless networks [8].

Multi-way massive MIMO relay networks—the combination of multi-way relaying and massive MIMO technologies—offer very high throughput, communication reliability, and energy efficiency, and have received increasing research interest recently [9,10]. In [9,10], the authors demonstrated that with a simple linear processing (e.g. zero-forcing and/or maximum-ratio processing) in the downlink and uplink data transmission, the system performance is nearly optimal. Furthermore, by using very large antenna arrays at the relay, the transmit power of each user and/or the relay can be scaled down proportionally to the number of relay antennas, while maintaining a desired quality-of-service [9,10].

In this paper, we consider a three-way massive MIMO relaying network which is the most simplified version of multi-way systems. Different with the aforementioned works, we focus on the aspects of transmission design for DF operation. We propose a new transmission protocol in which the broadcast phase needs only 1 time-slot to send all symbols to all users (the conventional scheme [11] requires 2 time-slots). We derive the sum spectral efficiency of our proposed scheme. Compared with the conventional scheme, our proposed scheme improves the sum spectral efficiency by a factor of 1.5.

Notation: Matrices and vectors are represented via upper- and lower-case boldface letters, respectively. The Hermitian transpose, Frobenius norm of matrix $\mathbf{Z}$, and expectation operator are denoted by $(\cdot)^H$, $\|\mathbf{Z}\|_{\mathrm{F}}$, and $\mathbb{E}\{\cdot\}$, respectively. The (m,n)-th element of matrix $\mathbf{Z}$ is denoted by z_{mn}. Finally, we use $\mathbf{z}_k$ to denote the k-th column of matrix $\mathbf{Z}$.

2 System Model

We consider a DF three-way massive MIMO relay system as shown in Fig. 1. The system includes one relay station having M antennas and 3 users, each having a single-antenna. The relay station helps the users to exchange their data under time-division duplex operation. We assume that the users have perfect channel state information (CSI) and they operate in half-duplex mode. We further assume that the direct channels from user-to-user do not exit due to large

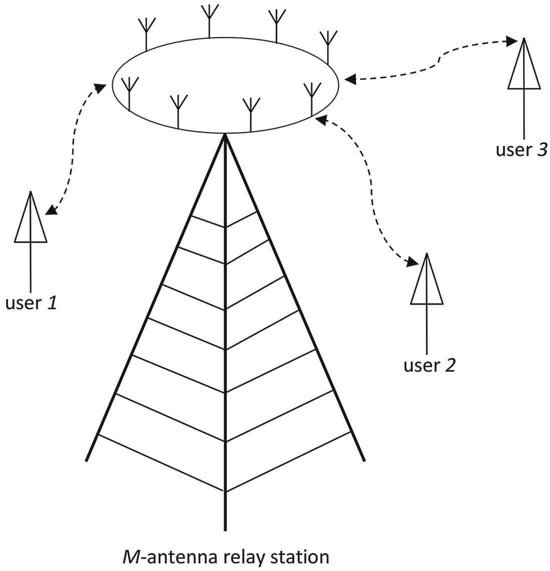

Fig. 1. Decode-and-forward three-way massive MIMO relay networks.

obstacle and/or heavy shadowing. The information exchange among three users is conducted via the relay station.

Regarding the channel model, we consider both large-scale fading (path loss and log-normal attenuation) and small-scale fading (Rayleigh fading). Let g_{mk} be the channel coefficient from the m-th antenna of the relay station and the k-th user, $m = 1, \ldots, M$, $k = 1, 2, 3$. Then g_{mk} can be represented by

$$g_{mk} = h_{mk}\sqrt{\beta_k}, \tag{1}$$

where $h_{mk} \sim \mathcal{CN}(0, 1)$ represents the small-scale fading and β_k represents the large-scale fading. We can see in (1) that the large-scale fading β_k does not depend on the antenna index m. This is reasonable since the distance between the users and the relay station is much greater than the distance between the antennas at the relay station.

Denote by $\mathbf{G} \in \mathbb{C}^{M\times 3}$ the channel matrix between the 3 users and M-antenna relay station. Then, from (1), we have

$$\mathbf{G} = \mathbf{H}\mathbf{D}^{1/2}, \tag{2}$$

where $\mathbf{H} \in \mathbb{C}^{M\times 3}$ is a $M \times 3$ small-scale matrix whose (m, k)-th element is $h_{m,k}$, and $\mathbf{D} \in \mathbb{C}$ is a 3×3 diagonal matrix of large-scale fading whose k-th diagonal element is β_k.

The transmission protocol is generally divided into two phases: multiple-access phase, and broadcast phase. In the first phase, all three users transmit their symbols to the relay station. Then, the relay station decodes all these symbols. In the second phase, the relay station sends the decoded symbols to all users. In what follows, we will introduce two different transmission protocols: conventional transmission scheme and proposed transmission scheme.

3 Multi-way Relaying with the Conventional Transmission Scheme

In this section, DF multi-way massive MIMO relaying with the conventional transmission protocol is presented. The corresponding spectral efficiency is also derived.

3.1 Multiple-Access Phase

In this phase, all 3 users transmit their bearing-data to the relay in the same time-frequency resource. The $M \times 1$ signal vector received at the relay is given by

$$\mathbf{y}_{\mathtt{R}} = \sqrt{\rho_{\mathrm{u}}}\mathbf{G}\mathbf{x} + \mathbf{n}_{\mathtt{R}}, \tag{3}$$

where ρ_{u} is the normalized transmit power at each user, $\mathbf{n}_{\mathtt{R}}$ is an AWGN vector whose elements are i.i.d. $\mathcal{CN}(0,1)$ random variables, and $\mathbf{x} \triangleq [x_1,\ x_2,\ x_3]^T$, with $\mathbb{E}\left\{|x_k|^2\right\} = 1$, is the vector of signals transmitted from 3 users to the relay.

To decode $\mathbf{x}$, the relay uses the maximum-ratio combining scheme. With maximum-ratio combining, the relay first multiply its received signal vector $\mathbf{y}_{\mathtt{R}}$ with $\mathbf{G}^H$ as

$$\begin{aligned} \mathbf{r} &= \mathbf{G}^H \mathbf{y}_{\mathtt{R}} \\ &= \sqrt{\rho_{\mathrm{u}}}\mathbf{G}^H\mathbf{G}\mathbf{x} + \mathbf{G}^H\mathbf{n}_{\mathtt{R}}. \end{aligned} \tag{4}$$

Then, it decodes each symbols x_1, x_2, and x_3 separately by considering each element of $\mathbf{r}$ as a point-to-point scalar channel. Denote by r_k the k-th component of $\mathbf{r}$. Then, from (4), we have

$$r_k = \sqrt{\rho_{\mathrm{u}}}\|\mathbf{g}_k\|^2 x_k + \sqrt{\rho_{\mathrm{u}}}\sum_{\substack{i=1\\ i\neq k}}^{K} \mathbf{g}_k^H\mathbf{g}_i x_i + \mathbf{g}_k^H\mathbf{n}_{\mathtt{R}}, \tag{5}$$

where $\mathbf{g}_k$ is the k-th column of $\mathbf{G}$. The k-th stream r_k will be used to decode x_k. Thus, the corresponding uplink spectral efficiency (measured in bit/s/Hz) is

$$\mathtt{R}^{\mathrm{ul}}_{\mathrm{cov},k} = \mathbb{E}\left\{\log_2\left(1 + \frac{\rho_{\mathrm{u}}\|\mathbf{g}_k\|^4}{\rho_{\mathrm{u}}\sum\limits_{\substack{i=1\\ i\neq k}}^{3}\left|\mathbf{g}_k^H\mathbf{g}_i\right|^2 + \|\mathbf{g}_k\|^2}\right)\right\}. \tag{6}$$

3.2 Broadcast Phase

In this phase, the symbols, which are decoded at the relay in the multiple-access phase, are broadcasted from the relay to all users in 2 time-slots.

(1) First time-slot: The relay wants to transmit symbol $x_{j(k,1)}$ to the k-th user, $k = 1, \ldots, 3$, where

$$j(k,1) \triangleq \begin{cases} (k+1) \text{ modulo } 3, & \text{if } (k+1) \neq 3 \\ 3, & \text{otherwise.} \end{cases} \tag{7}$$

Therefore, the transmitted signal vector from the relay in the first time-slot is

$$\mathbf{s}^{(1)} = \sqrt{\frac{\rho_{\mathrm{r}}}{M \sum_{i=1}^{3} \beta_i}} \sum_{i=1}^{3} \mathbf{g}_i x_{j(i,1)}, \tag{8}$$

where ρ_{r} is the normalized transmit power at the relay. Note that the constant $\sqrt{\frac{\rho_{\mathrm{r}}}{M \sum_{i=1}^{3} \beta_i}}$ in (8) is chosen to satisfy that the transmitted power at the relay is ρ_{r}, i.e., $\mathbb{E}\left\{\|\mathbf{s}^{(1)}\|^2\right\} = \rho_{\mathrm{r}}$.

With the transmitted signal vector given in (8), the received signal at the k-th user is given by

$$\begin{aligned} y_k^{(1)} &= \mathbf{g}_k^H \mathbf{s}^{(1)} + n_k^{(1)} \\ &= \sqrt{\frac{\rho_{\mathrm{r}}}{M \sum_{i=1}^{3} \beta_i}} \sum_{i=1}^{3} \mathbf{g}_k^H \mathbf{g}_i x_{j(i,1)} + n_k^{(1)}. \end{aligned} \tag{9}$$

Since the k-th user knows its transmitted symbol x_k (or $x_{j(k-1,1)}$) and has perfect CSI, it can subtract self-interference before detecting the desired symbol $x_{j(k,1)}$. From (9), the received signal after removing self-interference is

$$\begin{aligned} \tilde{y}_k^{(1)} &\triangleq y_k^{(1)} - \sqrt{\frac{\rho_{\mathrm{r}}}{M \sum_{i=1}^{3} \beta_i}} \mathbf{g}_k^H \mathbf{g}_{j(k+1,1)} x_{j(k-1,1)} \\ &= \sqrt{\frac{\rho_{\mathrm{r}}}{M \sum_{i=1}^{3} \beta_i}} \|\mathbf{g}_k\|^2 x_{j(k,1)} + \sqrt{\frac{\rho_{\mathrm{r}}}{M \sum_{i=1}^{3} \beta_i}} \sum_{\substack{i=1 \\ j(i,1) \neq j(k,1), j(k-1,1)}}^{3} \mathbf{g}_k^H \mathbf{g}_i x_{j(i,1)} + n_k^{(1)}. \end{aligned} \tag{10}$$

Thus, we obtain the corresponding downlink spectral efficiency of the system in the first time-slot as follows:

$$\mathtt{R}_{\mathrm{cov},k}^{\mathrm{dl},(1)} = \mathbb{E}\left\{ \log_2 \left(1 + \frac{\frac{\rho_{\mathrm{r}}}{M \sum_{i=1}^{3} \beta_i} \|\mathbf{g}_k\|^4}{\frac{\rho_{\mathrm{r}}}{M \sum_{i=1}^{3} \beta_i} \sum\limits_{\substack{i=1 \\ j(i,1) \neq j(k,1), j(k-1,1)}}^{3} \left|\mathbf{g}_k^H \mathbf{g}_i\right|^2 + 1} \right) \right\}. \tag{11}$$

(2) Second time-slot: The relay wants to transmit symbol $x_{j(k,2)}$ to the k-th user, where

$$j(k,2) \triangleq \begin{cases} (k+2) \text{ modulo } 3, & \text{if } (k+2) \neq 3 \\ 3, & \text{otherwise.} \end{cases} \tag{12}$$

Thus, the transmitted signal vector from the relay in the second time-slot is

$$\mathbf{s}^{(2)} = \sqrt{\frac{\rho_{\mathrm{r}}}{M \sum_{i=1}^{3} \beta_i}} \sum_{i=1}^{3} \mathbf{g}_i x_{j(i,2)}, \tag{13}$$

and the received signal at the k-th user is given by

$$\begin{aligned} y_k^{(2)} &= \mathbf{g}_k^H \mathbf{s}^{(2)} + n_k^{(2)} \\ &= \sqrt{\frac{\rho_{\mathrm{r}}}{M \sum_{i=1}^{3} \beta_i}} \sum_{i=1}^{3} \mathbf{g}_k^H \mathbf{g}_i x_{j(i,2)} + n_k^{(2)}. \end{aligned} \tag{14}$$

Since the k-th user knows perfect CSI and its transmitted symbol x_k (or $x_{j(k-2,2)}$), it can subtract self-interference prior to detecting the desired symbol $x_{j(k,2)}$. The received signal after removing self-interference is

$$\tilde{y}_k^{(2)} = \sqrt{\frac{\rho_{\mathrm{r}}}{M \sum_{i=1}^{3} \beta_i}} \|\mathbf{g}_k\|^2 x_{j(k,2)} + \sqrt{\frac{\rho_{\mathrm{r}}}{M \sum_{i=1}^{3} \beta_i}} \sum_{\substack{i=1 \\ j(i,2) \neq j(k,2), j(k-2,2)}}^{3} \mathbf{g}_k^H \mathbf{g}_i x_{j(i,2)} + n_k^{(2)}. \tag{15}$$

Therefore, we obtain the corresponding downlink spectral efficiency of the system in the second time-slot as

$$\mathtt{R}_{\mathrm{cov},k}^{\mathrm{dl},(2)} = \mathbb{E}\left\{ \log_2 \left(1 + \frac{\frac{\rho_{\mathrm{r}}}{M \sum_{i=1}^{3} \beta_i} \|\mathbf{g}_k\|^4}{\frac{\rho_{\mathrm{r}}}{M \sum_{i=1}^{3} \beta_i} \sum\limits_{\substack{i=1 \\ j(i,2) \neq j(k,2), j(k-2,2)}}^{3} \left| \mathbf{g}_k^H \mathbf{g}_i \right|^2 + 1} \right) \right\}. \tag{16}$$

From (6), (11), and (16), the sum spectral efficiency of the conventional scheme is given

$$\mathtt{SE}_{\mathrm{cov}} = \frac{1}{3} \sum_{k=1}^{3} \sum_{t=1}^{2} \min \left(\mathtt{R}_{\mathrm{cov},k}^{\mathrm{ul}}, \mathtt{R}_{\mathrm{cov},k}^{\mathrm{dl},(t)} \right). \tag{17}$$

The pre-log factor 1/3 in (17) comes from the fact that we spend 3 time-slots to exchange all symbols to 3 users.

4 Proposed Scheme: Multi-way Relaying with Successive Cancelation Decoding

In this section, a novel technical transmission protocol is proposed by using successive the cancelation decoding method. With our proposed scheme, we need only one time-for the broadcast phase.

4.1 Multiple-Access Phase

Follow the same transmission protocol as in the multiple-access phase of the conventional scheme. See Sect. 3.1. Therefore, the uplink spectral efficiency is

$$\mathtt{R}_{\text{new},k}^{\text{ul}} = \mathbb{E}\left\{\log_2\left(1 + \frac{\rho_{\text{u}}\|\mathbf{g}_k\|^4}{\rho_{\text{u}}\sum\limits_{\substack{i=1\\i\neq k}}^{3}\left|\mathbf{g}_k^H\mathbf{g}_i\right|^2 + \|\mathbf{g}_k\|^2}\right)\right\}. \tag{18}$$

4.2 Broadcast Phase

In section, we propose a new broadcast scheme which needs only 1 time-slot to transmit all symbols to all users. The detail of this technique is given as follows.

The transmitted signal vector from the relay is given by

$$\mathbf{s} = \sqrt{\frac{\rho_{\text{r}}}{M\sum_{i=1}^{3}\beta_i}}\sum_{i=1}^{3}\mathbf{g}_i x_{j(i,1)}. \tag{19}$$

where $j(i,1)$ is defined in (7).

(1) The first user: From (19), the received signal at the first user is

$$\begin{aligned} y_1 &= \mathbf{g}_1^H\mathbf{s} + n_1 \\ &= \sqrt{\frac{\rho_{\text{r}}}{M\sum_{i=1}^{3}\beta_i}}\sum_{i=1}^{3}\mathbf{g}_1^H\mathbf{g}_i x_{j(i,1)} + n_1. \end{aligned} \tag{20}$$

Again, by using self-interference cancelation scheme, the received signal at user 1 after removing self-interference is

$$\tilde{y}_1 = \sqrt{\frac{\rho_{\text{r}}}{M\sum_{i=1}^{3}\beta_i}}\|\mathbf{g}_1\|^2 x_2 + \sqrt{\frac{\rho_{\text{r}}}{M\sum_{i=1}^{3}\beta_i}}\mathbf{g}_1^H\mathbf{g}_2 x_3 + n_1, \tag{21}$$

and the downlink spectral efficiency for the first user to decode x_2 is

$$\mathtt{R}_{\text{new},1}^{\text{dl},(1)} = \mathbb{E}\left\{\log_2\left(1 + \frac{\frac{\rho_{\text{r}}}{M\sum_{i=1}^{3}\beta_i}\|\mathbf{g}_1\|^4}{\frac{\rho_{\text{r}}}{M\sum_{i=1}^{3}\beta_i}\left|\mathbf{g}_1^H\mathbf{g}_2\right|^2 + 1}\right)\right\}. \tag{22}$$

After decoding x_2, user 1 knows signal transmitted from user 2, and hence, it can remove symbol x_2. Thus, the received signal at the first user after canceling x_2 is

$$\tilde{\tilde{y}}_1 = \sqrt{\frac{\rho_{\mathrm{r}}}{M\sum_{i=1}^{3}\beta_i}}\mathbf{g}_1^H\mathbf{g}_2 x_3 + n_1. \tag{23}$$

Therefore, the downlink spectral efficiency of the first user to decode x_3 is given by

$$\mathtt{R}_{\mathrm{new},1}^{\mathrm{dl},(2)} = \mathbb{E}\left\{\log_2\left(1 + \frac{\rho_{\mathrm{r}}}{M\sum_{i=1}^{3}\beta_i}\left|\mathbf{g}_1^H\mathbf{g}_2\right|^2\right)\right\}. \tag{24}$$

(2) The second user: Similarly, the received signal at the second user can be written as

$$\begin{aligned} y_2 &= \mathbf{g}_2^H\mathbf{s} + n_2 \\ &= \sqrt{\frac{\rho_{\mathrm{r}}}{M\sum_{i=1}^{3}\beta_i}}\sum_{i=1}^{3}\mathbf{g}_2^H\mathbf{g}_i x_{j(i,1)} + n_2. \end{aligned} \tag{25}$$

Since, user 2 knows its transmitted symbol x_2, it can subtract self-interference before detecting symbol x_3 transmitted from user 3. Therefore, the received signal at user 2 can be presented as

$$\tilde{y}_2 = \sqrt{\frac{\rho_{\mathrm{r}}}{M\sum_{i=1}^{3}\beta_i}}\|\mathbf{g}_2\|^2 x_3 + \sqrt{\frac{\rho_{\mathrm{r}}}{M\sum_{i=1}^{3}\beta_i}}\mathbf{g}_2^H\mathbf{g}_3 x_1 + n_2, \tag{26}$$

and then the downlink spectral efficiency for user 2 to decode x_3 is

$$\mathtt{R}_{\mathrm{new},2}^{\mathrm{dl},(1)} = \mathbb{E}\left\{\log_2\left(1 + \frac{\frac{\rho_{\mathrm{r}}}{M\sum_{i=1}^{3}\beta_i}\|\mathbf{g}_2\|^4}{\frac{\rho_{\mathrm{r}}}{M\sum_{i=1}^{3}\beta_i}\left|\mathbf{g}_2^H\mathbf{g}_3\right|^2 + 1}\right)\right\}. \tag{27}$$

After decoding x_3, user 2 knows the signal transmitted from user 3, and hence, it can eliminate the symbol x_3. Thus, the received signal at user 2 is

$$\tilde{\tilde{y}}_2 = \sqrt{\frac{\rho_{\mathrm{r}}}{M\sum_{i=1}^{3}\beta_i}}\mathbf{g}_2^H\mathbf{g}_3 x_1 + n_2, \tag{28}$$

and the corresponding downlink spectral efficiency is given by

$$\mathtt{R}_{\mathrm{new},2}^{\mathrm{dl},(2)} = \mathbb{E}\left\{\log_2\left(1 + \frac{\rho_{\mathrm{r}}}{M\sum_{i=1}^{3}\beta_i}\left|\mathbf{g}_2^H\mathbf{g}_3\right|^2\right)\right\}. \tag{29}$$

(3) The third user: With the same methodology, the received signal at the third user can be written as

$$\begin{aligned} y_3 &= \mathbf{g}_3^H \mathbf{s} + n_3 \\ &= \sqrt{\frac{\rho_{\mathrm{r}}}{M \sum_{i=1}^{3} \beta_i}} \sum_{i=1}^{3} \mathbf{g}_3^H \mathbf{g}_i x_{j(i,1)} + n_3. \end{aligned} \tag{30}$$

Since user three knows its transmitted signal, it can subtract self-interference before detecting x_1. The received signal at user 3 after self-interference cancelation is

$$\tilde{y}_3 = \sqrt{\frac{\rho_{\mathrm{r}}}{M \sum_{i=1}^{3} \beta_i}} \|\mathbf{g}_3\|^2 x_1 + \sqrt{\frac{\rho_{\mathrm{r}}}{M \sum_{i=1}^{3} \beta_i}} \mathbf{g}_3^H \mathbf{g}_1 x_2 + n_3, \tag{31}$$

then the downlink spectral efficiency for user 3 to decode x_1 is

$$\mathtt{R}_{\mathrm{new},3}^{\mathrm{dl},(1)} = \mathbb{E}\left\{ \log_2 \left(1 + \frac{\frac{\rho_{\mathrm{r}}}{M \sum_{i=1}^{3} \beta_i} \|\mathbf{g}_3\|^4}{\frac{\rho_{\mathrm{r}}}{M \sum_{i=1}^{3} \beta_i} \left|\mathbf{g}_3^H \mathbf{g}_1\right|^2 + 1} \right) \right\}. \tag{32}$$

After decoding x_1, user 3 can subtract x_1 to obtain

$$\tilde{\tilde{y}}_3 = \sqrt{\frac{\rho_{\mathrm{r}}}{M \sum_{i=1}^{3} \beta_i}} \mathbf{g}_3^H \mathbf{g}_1 x_2 + n_3. \tag{33}$$

Therefore, the downlink spectral efficiency for user 3 to decode x_2 is given by

$$\mathtt{R}_{\mathrm{new},3}^{\mathrm{dl},(2)} = \mathbb{E}\left\{ \log_2 \left(1 + \frac{\rho_{\mathrm{r}}}{M \sum_{i=1}^{3} \beta_i} \left|\mathbf{g}_3^H \mathbf{g}_1\right|^2 \right) \right\}. \tag{34}$$

From (18), (22), (24), (27), (29), (32), and (34), we obtain the sum spectral efficiency for our proposed scheme as

$$\mathtt{SE}_{\mathrm{new}} = \frac{1}{2} \sum_{k=1}^{3} \sum_{t=1}^{2} \min \left(\mathtt{R}_{\mathrm{new},k}^{\mathrm{ul}}, \mathtt{R}_{\mathrm{new},k}^{\mathrm{dl},(t)} \right). \tag{35}$$

The pre-log factor of (35) is 1/2. This comes from the fact that we spend 2 time-slots to exchange all symbols to 3 users. Compared with the conventional scheme (17), our proposed scheme improves the pre-log factor 1.5 times, and hence, may improve the sum spectral efficiency significantly.

5 Numerical Results

In this section, the numerical results are provided to verify the benefit of our proposed scheme. We focus on the sum spectral efficiency defined in (17) and (35).

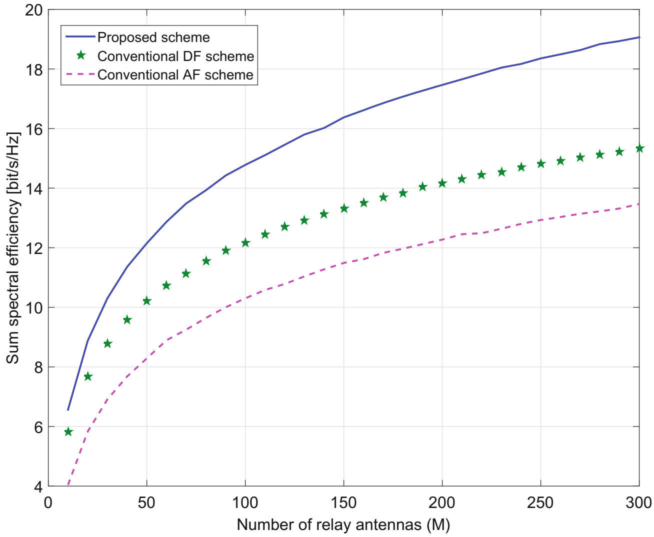

Fig. 2. The comparison of spectral efficiency of different schemes versus the number of relay antennas. We choose $\rho_{\mathrm{u}} = 0$ dB, $\rho_{\mathrm{r}} = 10$ dB, $\beta_k = 1$.

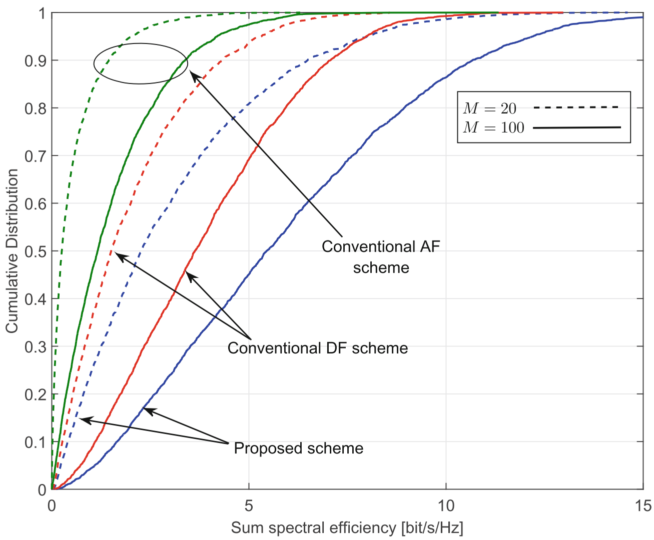

Fig. 3. The comparison of cumulative distribution for different schemes versus sum spectral efficiency. We choose $\rho_{\mathrm{u}} = 0$ dB, $\rho_{\mathrm{r}} = 10$ dB, $M = 100$.

First we consider a simple scenario where the large-scale fading is neglected, i.e. $\beta_1 = \beta_2 = \beta_3 = 1$. We compare the sum spectral efficiency of our proposed scheme with those of the conventional scheme given in Sect. 3.2 and the conventional scheme with AF mode given in [11]. Figure 2 shows the sum spectral efficiency of our proposed scheme, conventional DF scheme (see Sect. 3.2), and conventional AF scheme [11] versus the number of relay antennas, with $\rho_{\mathrm{u}} = 0$ dB and $\rho_{\mathrm{r}} = 10$ dB. Clearly, our proposed scheme is much better than other schemes. The reason is that, our proposed scheme needs only 2 time-slots to exchange the bearing-information among 3 users, while the conventional scheme needs 3 time-slots. The conventional DF scheme is better than the conventional AF scheme since with AF, the noise and interference of the multiple-access phase is amplified. Furthermore, we can see that the sum spectral efficiency increases significantly when the number of relay antennas increases.

We next investigate a more realistic scenario in which the large-scale fading β_k is modeled by path loss and lognormal shadowing. In order to generate the large-scale fading, we follow the same model presented in [10]. Figure 3 shows the comparison of three transmission schemes as in Fig. 2 via the cumulative distribution of the sum spectral efficiency. We can see that the sum spectral efficiency of our proposed scheme outperforms other schemes. The performance gap increases when the number of relay antennas increases. In particular, when $M = 100$, the 95%-likely sum spectral efficiency of our proposed scheme is around 1.5 times and 5 times higher than those of the conventional DF scheme and the conventional AF scheme, respectively.

6 Conclusion

In this paper, we investigated a DF three-way massive MIMO relay system under time-division duplex operation. A novel transmission protocol was proposed to reduce the number of time-slots for exchanging data among the users. Our proposed scheme relied on success cancelation decoding, and hence, needs only 2 time-slots, while the conventional scheme requires 3 time-slots. The sum spectral efficiency of our proposed scheme was derived. We showed that our proposed scheme offers much higher sum spectral efficiency than the conventional AF and DF schemes do.

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