Spectral and Energy Efficiency for Massive MIMO Multi-Pair Two-Way Relay Networks with ZFR/ZFT and Imperfect CSI

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***Abstract*—This paper investigates a massive MIMO multi-pair two-way relay system, where K-pair users exchange information within communication pair, with the help of a shared amplify-and-forward (AF) relay station (RS). Large scale antenna array is equipped at the RS and each user has a signal antenna. The RS adopts the zero-forcing reception/zero-forcing transmission (ZFR/ZFT) beamforming. The imperfect channel state information (CSI) is considered, and the impact of channel estimation errors on system performances is investigated. Based on two power scaling schemes, we obtain the asymptotic spectral efficiency and asymptotic energy efficiency of the considered system. Our results reveal that when the number of RS antennas grows without bound, the small-fading can be averaged out; the additional noise and residual self-interference generated by channel estimation errors will completely disappear; and inter-pair interference will also vanish. Consequently, the simulation results will be confirmed by Monte-Carlo simulation method.**

***Keywords*–Massive MIMO, Two-way relaying, Imperfect CSI, Energy efficiency, Spectral efficiency**

I. Introduction

For future “5G” wireless communication systems, massive MIMO has attracted much attention for significantly boosting capacity and reducing the total transmit power, where a base station using antenna arrays with a few hundred antennas serves tens of users [1] [2]. Such system can efficiently reduce the effect of noise, intra-cell interference and fast fading just using simple linear signal processing approaches [3] [4]. Therefore, massive MIMO has been extensively investigated for its significant advantages [5]–[7]. In [5], the user ergodic achievable uplink data rate with linear detectors was discussed, as well as the spectral efficiency (SE) and energy efficiency (EE) tradeoff. In [6], the power scaling law for massive MIMO systems in Ricean fading channels were proposed and then the uplink rates with unlimited number of the base station antennas were studied. An efficient channel estimation scheme called beamforming training and precoding techniques to evaluate the SE were considered in [7].

On the other hand, cooperative relaying has been extensively explored for expanding coverage and increasing diversity gain without any power increase [8] [9]. Amongst them, two-way relaying has gained great research interest due to the high EE. In a two-way relaying system, two users synchronously transmit their individual signals to the relay station (RS) during the multiple-access (MA) phase and the RS broadcasts the received signals to the two users during the broadcast (BC) phase. Not surprisingly, massive MIMO introduced into the two-way relaying system can be regarded as a strong candidate for improving the system performance, such as SE and EE [5] [10]. In [11], the system average ergodic achievable rates in four power allocation scenarios were conducted with a large relay antenna array. In [12], both asymptotic SE and EE were compared with two classical beamforming and three power scale schemes.

However, in the practical relaying system, we cannot obtain the perfect CSI because of the estimation error, feedback delay, and so on. Fortunately, some researches with imperfect CSI in the massive MIMO relaying network have been emerged during these decades [8], [13], [14]. With the imperfect CSI, [8] presented an optimal power allocation scheme for the maximum EE with a given SE. In [13], the average system bit error rate and system outage probability were derived based on the channel estimation error. The asymptotic system outage probability with a high SNR under the impact of imperfect CSI was derived in [14].

In this paper, we investigate the SE and EE of the multi-pair massive MIMO two-way relaying system with imperfect CSI, where K-pair single-antenna users communicate within user-pair by a RS with N antennas, where $N \gg 2K$. In our system, AF protocol and zero-forcing reception/zero-forcing transmission (ZFR/ZFT) beamforming are adopted. Additionally, because of the antenna array gain, the power of each user or both all users and RS can be inversely proportional to N with no reduction in the system performance, thus two power scaling schemes are considered. Based on the aforementioned conditions, the asymptotic signal to inference and noise ratio (SINR) is firstly deduced and thus the asymptotic SE and EE can be obtained. Our analysis results show that when the relaying antenna number approaches to infinity, the small-scale fading will be averaged out; the residual interference, self-interference and additional noise caused by the channel estimation will pass away. In addition, imperfect CSI will degrade the asymptotic SE and EE of the considered system. Finally, Monte-Carlo simulations are employed to verify our results.

Notation: $(\cdot)^H, (\cdot)^T, (\cdot)^*, (\cdot)^{-1}, \mathrm{Tr}(\cdot)$ and $\|\cdot\|$ denote the conjugate transpose, the transpose, the conjugate, the inverse, the trace and the Euclidean norm of a matrix, respectively. $\mathbb{E}\{\mathbf{x}\}$ represents the expectation of a random variable $\mathbf{x}$. $\mathbf{I}_N$ denotes an $N \times N$ identity matrix. $\mathcal{CN}(\mu, \sigma_n^2)$ is the complex-Gaussian distribution with mean μ and variance σ_n^2. The notation $\xrightarrow[N\to\infty]{a.s.}$ and notation $\xrightarrow[N\to\infty]{d}$ denote the almost sure convergence and the convergence in distribution with the unlimited number N, respectively.

II. System Model

In a massive MIMO multi-pair two-way relaying system, $2K$ users making up K communication pairs exchange information within pair by a shared AF RS. In such a system, each user has a single antenna while the RS is equipped with hundreds of antennas. The user k and user k' are considered as a communication pair (k, k'), in which two users exchange information with each other. Therefore, we can denote the ith communication pair $(2i-1, 2i), i = 1, \ldots, K$. The whole communication transmission occupies two phases, i.e., the MA phase and the BC phase.

In the first MA phase, all $2K$ users synchronously transmit their individual signals to the RS, then the received signal vector can be written as

$$\mathbf{y}_r = \sum_{i=1}^{2K} \mathbf{g}_i \sqrt{P_U} x_i + \mathbf{n}_r = \sqrt{P_U}\mathbf{G}\mathbf{x} + \mathbf{n}_r, \tag{1}$$

where $\mathbf{y}_r \in \mathbb{C}^{N\times 1}$, $\mathbf{x} = [x_1, \ldots, x_{2K}]^T$ represents transmitted symbols with $\mathbb{E}\{\mathbf{x}\mathbf{x}^H\} = \mathbf{I}_{2K}$. Furthermore, $\mathbf{n}_r \in \mathbb{C}^{N\times 1}$ denotes the additive white Gaussian noise (AWGN) with zero-mean at the RS with $\mathbb{E}\{\mathbf{n}_r\mathbf{n}_r^H\} = \sigma_n^2\mathbf{I}_N$, and P_U is the transmit power constraint of each user. The channel matrix between the RS and all $2K$ users is expressed as $\mathbf{G} = [\mathbf{g}_1, \ldots, \mathbf{g}_{2K}] = \mathbf{H}\mathbf{D}^{1/2} \in \mathbb{C}^{N\times 2K}$, where $\mathbf{H} \in \mathbb{C}^{N\times 2K}$ represents the normalized small-scale fading channel matrix between the RS and all users, and $\mathbf{D} \in \mathbb{C}^{2K\times 2K}$ is the diagonal large-scale fading channel matrix with $[\mathbf{D}]_{kk} = \eta_k$. The kth column of the channel matrix $\mathbf{G}$, i.e., $\mathbf{g}_k$ satisfies the distribution of $\mathcal{CN}(0, \eta_k\mathbf{I}_N)$. Here we assume that all channels between the RS and $2K$ users will follow i.i.d. Rayleigh fading. The channel reciprocity is also assumed.

During the second BC phase, the RS amplifies the received signal which is given by $\mathbf{y} = \mathbf{F}\mathbf{y}_r$, where $\mathbf{F} \in \mathbb{C}^{N\times N}$ is the beamforming matrix. Then the RS broadcasts the processed signal back to $2K$ users. Besides, the RS should satisfy the transmit power constraint, i.e., $P_R = \mathrm{Tr}\left(\mathbb{E}\{\mathbf{y}\mathbf{y}^H\}\right)$.

Therefore, the received signal at the k'th user, $y_{k'}$, is expressed as

$$\begin{aligned} y_{k'} &= \mathbf{g}_{k'}^T\mathbf{y} + n_{k'} \\ &= \mathbf{g}_{k'}^T\mathbf{F}\mathbf{g}_k\sqrt{P_U}x_k + \mathbf{g}_{k'}^T\mathbf{F}\mathbf{g}_{k'}\sqrt{P_U}x_{k'} \\ &+ \mathbf{g}_{k'}^T\mathbf{F}\sum_{i\neq k,k'}^{2K}\mathbf{g}_i\sqrt{P_U}x_i + \mathbf{g}_{k'}^T\mathbf{F}\mathbf{n}_r + n_{k'}, \end{aligned} \tag{2}$$

where $n_{k'} \sim \mathcal{CN}(0, \sigma_n^2)$ denotes the AWGN at the k' user.

In Practice, the CSIs at RS may always be imperfect due to channel estimation errors and feedback delay, and so on. In this paper, we adopt the ZFR/ZFT beamforming at the RS which is expressed by the channel estimation matrix. The relation between actual channel $\mathbf{g}_k$ and its estimator $\hat{\mathbf{g}}_k$ is written as [15]

$$\mathbf{g}_k = \hat{\mathbf{g}}_k + \mathbf{e}_k, \tag{3}$$

where $\mathbf{e}_k \sim \mathcal{CN}\left(0, \sigma_{e_k}^2\mathbf{I}_N\right)$ is the channel estimation error vector independent of $\hat{\mathbf{g}}_k$ and $\hat{\mathbf{g}}_k \sim \mathcal{CN}\left(0, \left(\eta_k - \sigma_{e_k}^2\right)\mathbf{I}_N\right)$.

According to the channel estimations, the ZFR/ZFT beamforming matrix is given by [16]

$$\mathbf{F} = \beta_{zf}\hat{\mathbf{G}}^*(\hat{\mathbf{G}}^T\hat{\mathbf{G}}^*)^{-1}\mathbf{P}(\hat{\mathbf{G}}^H\hat{\mathbf{G}})^{-1}\hat{\mathbf{G}}^H \tag{4}$$

where β_{zf} is the amplification factor to satisfy the relaying transmit power constraint; the superscript "-1" denotes the inverse of matrix; $\mathbf{P}$ is the block diagonal matrix, i.e., $\mathbf{P} = \mathrm{diag}\{\mathbf{P}_1, \ldots, \mathbf{P}_K\}$ and $\mathbf{P}_i = [0\ 1; 1\ 0], i = 1, \ldots, K$.

The k'th user will cancel the self-interference term $\hat{\mathbf{g}}_{k'}^T\mathbf{F}\hat{\mathbf{g}}_{k'}\sqrt{P_U}x_{k'}$. However, due to the existence of the channel estimation error, the residual self-interference and additional noise will remain at the k'th user. After the self-interference cancelation, the remaining received signal at the k'th user is written in (5) in the top of next page.

Consequently, the SINR at the k'th user is

$$\gamma_{k'} = \frac{P_U|\hat{\mathbf{g}}_{k'}^T\mathbf{F}\hat{\mathbf{g}}_k|^2}{\mathrm{P_N} + \mathrm{P_A} + \mathrm{P_{II}} + \mathrm{P_{SI}}}, \tag{6}$$

where

$$\mathrm{P_N} = \sigma_n^2\left(\|\hat{\mathbf{g}}_{k'}^T\mathbf{F}\|^2 + \|\mathbf{e}_{k'}^T\mathbf{F}\|^2\right) + \sigma_n^2,$$

$$\mathrm{P_A} = P_U\left(|\hat{\mathbf{g}}_{k'}^T\mathbf{F}\mathbf{e}_k|^2 + |\mathbf{e}_{k'}^T\mathbf{F}\hat{\mathbf{g}}_k|^2 + |\mathbf{e}_{k'}^T\mathbf{F}\mathbf{e}_k|^2\right),$$

$$\mathrm{P_{II}} = P_U\sum_{i\neq k,k'}^{2K}\left(|\hat{\mathbf{g}}_{k'}^T\mathbf{F}\hat{\mathbf{g}}_i|^2 + |\hat{\mathbf{g}}_{k'}^T\mathbf{F}\mathbf{e}_i|^2 + |\mathbf{e}_{k'}^T\mathbf{F}\hat{\mathbf{g}}_i|^2 + |\mathbf{e}_{k'}^T\mathbf{F}\mathbf{e}_i|^2\right),$$

$$\mathrm{P_{SI}} = P_U\left(|\hat{\mathbf{g}}_{k'}^T\mathbf{F}\mathbf{e}_{k'}|^2 + |\mathbf{e}_{k'}^T\mathbf{F}\hat{\mathbf{g}}_{k'}|^2 + |\mathbf{e}_{k'}^T\mathbf{F}\mathbf{e}_{k'}|^2\right),$$

represent the power of AWGN, the power of additional noise, the power of inter-pair interference and the power of residual self-interference, respectively.

From (6), the SE of the multi-pair large-scale MIMO two-way relaying system is defined as

$$R = \frac{1}{2}\mathbb{E}\left[\sum_{i=1}^{2K}\log_2(1+\gamma_i)\right], \tag{7}$$

where the coefficient 1/2 means the communication transmission within a user pair occupies two phases. Therefore, the EE of the considered system is expressed as

$$\rho = \frac{R}{2KP_U + P_R}, \tag{8}$$

where $2KP_U + P_R$ denotes the total power consumption of all $2K$ users and the RS.

$$\begin{aligned} y_{c,k'} &= y_{k'} - \hat{\mathbf{g}}_{k'}^T \mathbf{F} \hat{\mathbf{g}}_{k'} \sqrt{P_U} x_{k'} \\ &= \underbrace{\hat{\mathbf{g}}_{k'}^T \mathbf{F} \hat{\mathbf{g}}_k \sqrt{P_U} x_k}_{\text{signal}} + \underbrace{\hat{\mathbf{g}}_{k'}^T \mathbf{F} \mathbf{e}_k \sqrt{P_U} x_k + \mathbf{e}_{k'}^T \mathbf{F} \hat{\mathbf{g}}_k \sqrt{P_U} x_k + \mathbf{e}_{k'}^T \mathbf{F} \mathbf{e}_k \sqrt{P_U} x_k}_{\text{(additional noise)}} + \underbrace{\left(\hat{\mathbf{g}}_{k'}^T + \mathbf{e}_{k'}^T\right) \mathbf{F} \mathbf{n}_r + n_{k'}}_{\text{(noise)}} \\ &+ \underbrace{\hat{\mathbf{g}}_{k'}^T \mathbf{F} \mathbf{e}_{k'} \sqrt{P_U} x_{k'} + \mathbf{e}_{k'}^T \mathbf{F} \hat{\mathbf{g}}_{k'} \sqrt{P_U} x_{k'} + \mathbf{e}_{k'}^T \mathbf{F} \mathbf{e}_{k'} \sqrt{P_U} x_{k'}}_{\text{(residual self-interference)}} + \underbrace{\left(\hat{\mathbf{g}}_{k'}^T + \mathbf{e}_{k'}^T\right) \mathbf{F} \sum_{i \neq k,k'}^{2K} \left(\hat{\mathbf{g}}_i + \mathbf{e}_i\right) \sqrt{P_U} x_i}_{\text{(inter-pair interference)}}. \end{aligned} \tag{5}$$

III. Asymptotic Spectral and Energy Efficiencies for Large N

In this section, we consider two power scaling schemes for power saving. When $N \to \infty$, we firstly obtain the asymptotic SINR, then the asymptotic SE and EE can be immediately derived based on (7) and (8).

Theorem 1. *In Case I ($P_U = E_U/N, P_R = E_R$, E_U and E_R are fixed), when the number of RS antennas $N \to \infty$, the asymptotic SINR at user k' is presented as follows:*

$$\gamma_{1,k'}^{\text{zf}} \xrightarrow[N \to \infty]{a.s.} \gamma_{1,k'}^{\text{zfasm}} \tag{9}$$

where

$$\gamma_{1,k'}^{\text{zfasm}} = \frac{E_U \left(\eta_k - \sigma_{e_k}^2\right)}{\sigma_n^2}.$$

Proof:

Denoting $\mathbf{p} \triangleq [p_1, \ldots, p_N]^T$ and $\mathbf{q} \triangleq [q_1, \ldots, q_N]^T$ are the zero-mean i.i.d. complex Gaussian vectors with $\mathbb{E}\{|p_i|^2\} = \sigma_p^2$ and $\mathbb{E}\{|q_i|^2\} = \sigma_q^2$, and we have

$$\frac{1}{N} \mathbf{p}^H \mathbf{q} \xrightarrow[N \to \infty]{a.s.} \begin{cases} 0 & \text{if } \mathbf{p} \neq \mathbf{q}, \\ \sigma_p^2 & \text{if } \mathbf{p} = \mathbf{q}. \end{cases} \tag{10}$$

Due to the Lindeberg-Lévy central limit theorem, we obtain

$$\frac{1}{\sqrt{N}} \mathbf{p}^H \mathbf{q} \xrightarrow[N \to \infty]{d} \mathcal{CN}\left(0, \sigma_p^2 \sigma_q^2\right), \tag{11}$$

After some calculation using the properties of (10) and (11), we have

$$\begin{aligned} \frac{y_{c,k'}}{\sqrt{N}} &\xrightarrow[N \to \infty]{a.s.} \frac{\beta_{zf}}{N} \sqrt{E_U} x_k + \frac{\beta_{zf}}{N} \left(\eta_k - \sigma_{e_k}^2\right)^{-1} \frac{\hat{\mathbf{g}}_k^H \mathbf{n}_r}{\sqrt{N}} + \frac{n_{k'}}{\sqrt{N}} \\ &\xrightarrow[N \to \infty]{d} \frac{\beta_{zf}}{N} \sqrt{E_U} x_k + \frac{\beta_{zf}}{N} \left(\eta_k - \sigma_{e_k}^2\right)^{-1} \tilde{n}_g + \frac{n_{k'}}{\sqrt{N}}, \end{aligned} \tag{12}$$

where $\tilde{n}_g \sim \mathcal{CN}\left(0, \left(\eta_k - \sigma_{e_k}^2\right) \sigma_n^2\right)$.

Therefore, the asymptotic SINR for Case I can be derived. ■

Theorem 1 reveals that the transmit power of the users can be scaled down by $1/N$ without reduction in system performance due to the antenna array gain. When the number of RS antennas goes to infinity, the asymptotic SINR goes to deterministic. Additionally, the small-scaling fading can be averaged out because of the diversity gain of N antennas. Based on the large number law in (10), the inter-pair interference disappears because all channels of different pairs approach pairwise orthogonal; the residual self-interference and additional noise both diminish. Moreover, the term $n_{k'}/\sqrt{N}$ disappears as N runs to infinity. As a consequence, the asymptotic SINR for Case I is only limited by the average SNR E_U/σ_n^2, the channel estimation error and large-scale fading.

Theorem 2. *In case II ($P_U = E_U/N, P_R = E_R/N$, E_U and E_R are fixed), when the number of RS antennas $N \to \infty$, the asymptotic SINR at user k' is presented as follows:*

$$\gamma_{2,k'}^{\text{zf}} \xrightarrow[N \to \infty]{a.s.} \frac{\gamma_{1,k'}^{\text{zfasm}} \varphi}{\gamma_{1,k'}^{\text{zfasm}} + \varphi + \psi}, \tag{13}$$

where

$$\varphi = \frac{E_R}{\sigma_n^2 \sum\limits_{i=1}^{2K} (\eta_i - \sigma_{e_i}^2)^{-1}},$$

$$\psi = 2\left(\eta_k - \sigma_{e_k}^2\right) \sum_{i=1}^{K} \left(\eta_{2i-1} - \sigma_{e_{2i-1}}^2\right)^{-1} \left(\eta_{2i} - \sigma_{e_{2i}}^2\right)^{-1} \Big/ \sum_{i=1}^{2K} \left(\eta_i - \sigma_{e_i}^2\right)^{-1}.$$

Proof: According to (10) and (11), when $N \to \infty$, we obtain

$$\frac{\beta_{zf}}{\sqrt{N}} \xrightarrow[N \to \infty]{a.s.} \sqrt{\frac{E_R}{E_U \mathrm{Tr}\left(\left(\frac{\hat{\mathbf{G}}^T \hat{\mathbf{G}}^*}{N}\right)^{-1}\right) + \sigma_n^2 \mathrm{Tr}\left(\left(\frac{\hat{\mathbf{G}}^T \hat{\mathbf{G}}^*}{N}\right)^{-1} \mathbf{P} \left(\frac{\hat{\mathbf{G}}^H \hat{\mathbf{G}}}{N}\right)^{-1} \mathbf{P}\right)}} \tag{14}$$

And the asymptotic received signal at the k'th user can be written as

$$y_{c,k'} \xrightarrow[N \to \infty]{a.s.} \frac{\beta_{zf}}{\sqrt{N}} \sqrt{E_U} x_k + \frac{\beta_{zf}}{\sqrt{N}} (\eta_k - \sigma_{e_k}^2)^{-1} \tilde{n}_g + n_{k'} \tag{15}$$

After some simple mathematical calculation, Theorem 2 can be deduced. ■

From Theorem 2, we conclude that the transmit power of both the RS and users can be scaled down by $1/N$ without comprising the system performance because of the array gain of N antennas. Again, in the very large N regime, the SINR

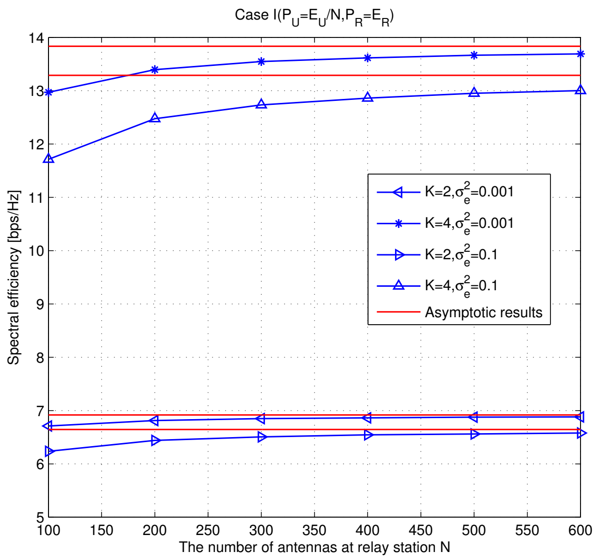

Fig. 1. Case I: The SE versus the number of antennas at RS N where $K = 2, 4$ and $\sigma_e^2 = 0.001, 0.1$.

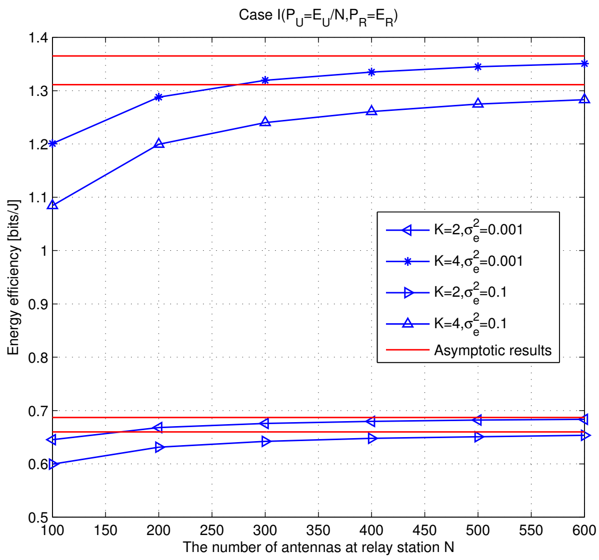

Fig. 2. Case I: The EE versus the number of antennas at RS N where $K = 2, 4$ and $\sigma_e^2 = 0.001, 0.1$.

for Case II becomes deterministic. In addition, the small-scaling fading can be averaged out due to the diversity gain of large scale antenna system; and the additional noise, inter-pair interference and residual self-interference eliminate due to the law of large number. However, different from Case I, it can be calculated that the asymptotic EE in Case II increases linearly with N; and the AWGN at the RS and users does not tend to zero when $N\to\infty$.

Remark: Assuming $\eta_i \gg \sigma_{e_i}^2, i = 1, 2, \cdots, 2K$. With the fact that $\frac{ab}{a+b+c} < \frac{ab}{a+b} \leq \min\{a, b\}$, where $a, b, c > 0$, the asymptotic SINR of $\gamma_{2,k'}^{\text{zf}}$ is smaller than $\gamma_{1,k'}^{\text{zfasm}}$. Therefore, the asymptotic EE in Case II is higher, whist Case I has the greater asymptotic SE between the two power scaling schemes.

IV. Simulation Results

In this section, the SE and EE of the massive MIMO multi-pair two-way relaying system are conducted by using Monte-Carlo simulations and then compared with our asymptotic analytical results. Assume that the system structure is symmetric, i.e., $\eta_i = 1$, $\sigma_{e_i}^2 = \sigma_e^2$, $i = 1, \ldots, 2K$. We consider that $E_U = E_R = 10$, the number of user pairs $K = 2, 4$, the noise variance $\sigma_n^2 = 1$ and the channel estimation error variance $\sigma_e^2 = 0.001, 0.1$ in all simulations.

The SE and EE versus the number of RS antennas N for Case I are plotted in Fig. 1 and 2, respectively. When $N \to \infty$, all the curves increase and tend to the corresponding high asymptotic constants since the small-scale fading is averaged out; the additional noise, residual self-interference and inter-pair interference eliminate, which is consistent with the mathematical analysis. Additionally, when σ_e^2 is set, both the asymptotic SE and EE will double by increasing K from 2 to 4. When we fix K, increasing σ_e^2 will degrade both SE and EE.

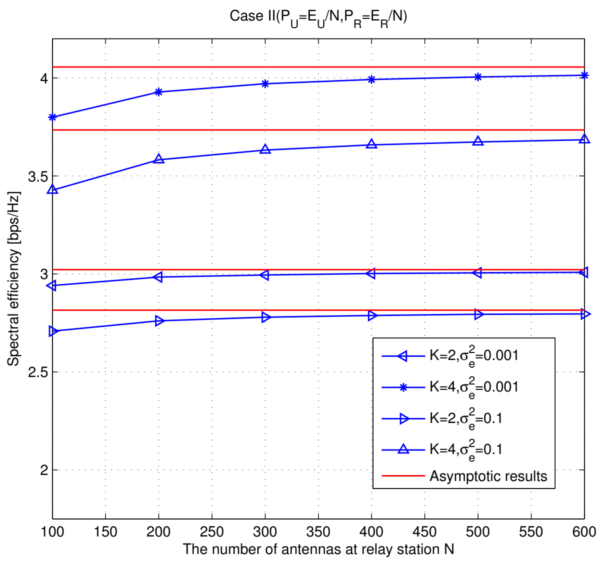

Fig. 3. Case II: The SE versus the number of antennas at RS N where $K = 2, 4$ and $\sigma_e^2 = 0.001, 0.1$.

For Case II, the SE and EE versus the number of RS antennas N are plotted in Fig. 3 and 4, respectively. From Fig. 3, the SE will converge to the high value without comprising the system performance with the unlimited antennas at the RS. Notably, When $N \to \infty$, the EE for Case II will increase linearly with N. These figures for Case II confirm that allocating large scale antennas at RS will improve the performance, because the small-scale fading can be averaged out; the additional noise, residual self-interference and inter-pair interference will go away with the unlimited RS antennas. Compared with above two power scaling schemes, Case I has

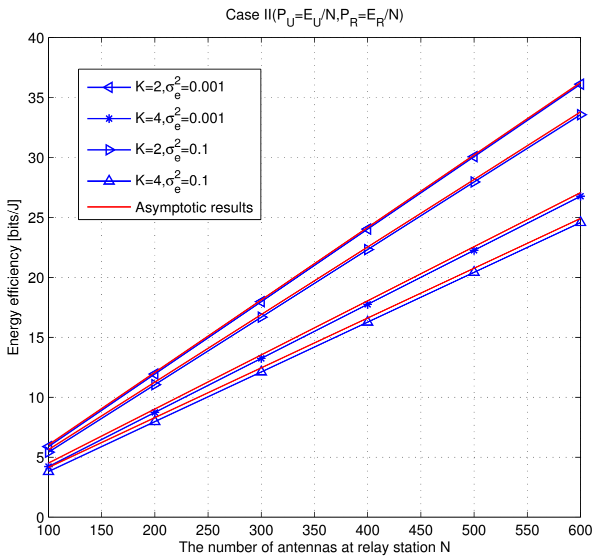

Fig. 4. Case II: The EE versus the number of antennas at RS N where $K = 2, 4$ and $\sigma_e^2 = 0.001, 0.1$.

the greater SE but the smaller EE.

V. Conclusion

In this paper, we have investigated the SE and EE of multi-pair two-way relaying system with large RS antennas under imperfect CSI. Based on AF protocol, we consider the classical beamforming ZFR/ZFT as well as two schemes of power-scaling. The analysis results of the system have been confirmed by Monte-Carlo simulation. Our study reveals that we can cut down the transmit power of the users or both the users and RS with the steady SE and the great EE. Additionally, the channel estimation error has a negative effect on the system performance. In the very large number of relay antennas regime, the small-scale fading can be averaged out because of the diversity gain of the large scale RS antennas; the additional noise, inter-pair interference and residual self-interference all disappear due to the law of large numbers.

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References

[1] M. Gauger, J. Hoydis, C. Hoek, H. Schlesinger, A. Pascht, and S. Brink, “Channel measurements with different antenna array geometries for massive mimo systems,” in *SCC 2015; 10th International ITG Conference on Systems, Communications and Coding; Proceedings of*, Hamburg, Germany, 2015, pp. 1–6.

[2] A. Burr and D. Fang, “Physical layer network coding for distributed massive mimo,” in *WSA 2015; 19th International ITG Workshop on Smart Antennas; Proceedings of*, Ilmenau, Germany, 2015, pp. 1–5.

[3] T. Marzetta, “Noncooperative cellular wireless with unlimited numbers of base station antennas,” *IEEE Trans. Wireless Commun.*, vol. 9, no. 11, pp. 3590–3600, 2010.

[4] H. Yang and T. L. Marzetta, “Performance of conjugate and zeroforcing beamforming in large-scale antenna systems,” *IEEE J. Sel. Areas Commun.*, vol. 31, no. 2, pp. 172–179, 2013.

[5] H. Q. Ngo, E. Larsson, and T. Marzetta, “Energy and spectral efficiency of very large multiuser mimo systems,” *Communications, IEEE Transactions on*, vol. 61, no. 4, pp. 1436–1449, 2013.

[6] Q. Zhang, S. Jin, K.-K. Wong, H. Zhu, and M. Matthaiou, “Power scaling of uplink massive mimo systems with arbitrary-rank channel means,” *IEEE journal of Selected Topics in Signal Processing*, vol. 8, no. 5, pp. 966–981, Oct. 2014.

[7] H. Q. Ngo, E. Larsson, and T. Marzetta, “Massive mu-mimo downlink tdd systems with linear precoding and downlink pilots,” in *Communication, Control, and Computing (Allerton), 2013 51st Annual Allerton Conference on*, Monticello, IL, 2013, pp. 293–298.

[8] H. Q. Ngo, H. Suraweera, M. Matthaiou, and E. Larsson, “Multipair full-duplex relaying with massive arrays and linear processing,” *Selected Areas in Communications, IEEE Journal on*, vol. 32, no. 9, pp. 1721–1737, 2014.

[9] H. A. Suraweera, H. Q. Ngo, T. Q. Duong, C. Yuen, and E. G. Larsson, “Multi-pair amplify-and-forward relaying with very large antenna arrays,” in *Proc. IEEE ICC2013*, Budapest, Jun. 2013, pp. 4635–4640.

[10] E. G. Larsson, F. Tufvesson, O. Edfors, and T. L. Marzetta, “Massive mimo for next generation wireless systems,” *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 186–195, 2014.

[11] X. Liang, S. Jin, X. Gao, and K.-K. Wong, “Ergodic rate analysis for multi-pair two-way relay large-scale antenna system,” in *Proc. IEEE ICC2014*, Sydney, NSW, Jun. 2014, pp. 5819–5824.

[12] H. Cui, L. Song, and B. Jiao, “Multi-pair two-way amplify-and-forward relaying with very large number of relay antennas,” *IEEE Trans. Wireless Commun.*, vol. 13, no. 5, pp. 2636–2645, May 2014.

[13] C. Wang, T.-K. Liu, and X. Dong, “Impact of channel estimation error on the performance of amplify-and-forward two-way relaying,” *Vehicular Technology, IEEE Transactions on*, vol. 61, no. 3, pp. 1197–1207, Mar. 2012.

[14] Q. Bu, J. Ge, and Y. Chen, “Outage performance for two-way af relaying with asymmetric date rate requirements and imperfect csi over nakagami-m fading,” in *Computer and Information Technology (CIT), 2014 IEEE International Conference on*, Xi’an, China, 2014, pp. 82–87.

[15] H. Yin, D. Gesbert, M. Filippou, and Y. Liu, “A coordinated approach to channel estimation in large-scale multiple-antenna systems,” *IEEE Journal on Selected Areas in Communications*, vol. 31, no. 2, pp. 264–273, Feb. 2013.

[16] Y.-C. Liang and R. Zhang, “Optimal analogue relaying with multi-antennas for physical layer network coding,” in *Proc. IEEE ICC2008*, Beijing, China, May 2008, pp. 3893–3897.