Performance Analysis of Large-scale MU-MIMO with AF Relaying in the Presence of Interference

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***Abstract*—This paper analyzes the performance of a large-scale multiuser multiple-input multiple-output (MU-MIMO) system with amplify-and-forward (AF) relaying in the presence of co-channel interference. Each user terminal (UT) has a single antenna while the relay is equipped with very large antenna arrays. To evaluate the impact of large number of relay antennas on the performance of the considered system, we derive a lower bound on the achievable rate. We also perform a large system analysis in the regimes of high signal-to-noise ratio (SNR), large number of relay antennas and large number of UTs. Numerical results are presented to verify the theoretical analysis.**

I. Introduction

Recently, there has been a great deal of interest in multiuser multiple-input multiple-output (MU-MIMO) systems with large-scale antenna arrays at the base station. Through the use of a large excess of service antennas over the number of active user terminals (UTs), large-scale MU-MIMO can average out thermal noise, fast channel fading and some interference, thus bring huge improvements in throughput, spectrum efficiency and energy efficiency even with very simple linear receivers [1]–[5]. Though large-scale MU-MIMO system is a promising network architecture, there are still entirely new challenges that need further research in the design and analysis of the technology.

On the other hand, relaying has also attracted significant attention in both academia and industry due to its numerous advantages. Most common relaying strategies proposed in the literature are decode-and-forward (DF) and amplify-and-forward (AF). Among various relaying methods, AF relaying in particular is preferred for its simplicity and low-cost implementation. Moreover, AF relaying is capable of suppressing co-channel interference (CCI) in practice [6].

An interesting practical scenario is that the relay is equipped with very large antenna arrays while each user terminal has a single antenna [7]. However, most of prior works deal with the case where all nodes are equipped with a single antenna, e.g. [8]. Also, in the context of single-antenna system, [9] investigated the impact of CCI on the performance of multi-hop AF relaying. Most recently, [10] analyzed a multi-pair full-duplex relaying system where the relay station is equipped with massive arrays, and [11] studied a multi-pair two-way AF relaying system with very large number of relay antennas. The limitations of [10] and [11] are the neglect of co-channel interferences in the system models. [12] investigated the outage performance of a dual-hop AF multiple antenna relaying system in the presence of CCI and additive white Gaussian noise (AWGN), and [13] proposed a two-hop AF relaying scheme and studied the outage probability of the system assuming CCI and thermal noise present at both the relay and the destination. However, it is worth noting that [12] and [13] only consider the scenario where only a single source node communicate with a single destination. A distributed AF relaying scheme is proposed in [14], and the asymptotic capacity increases without bound when each relay processes signals in a distributed manner. However, in the context of a single relay equipped with very large antenna arrays, the processing cannot be done distributedly at each antenna separately.

In this paper, we consider a large-scale MU-MIMO system with AF relaying where a group of K sources and K destinations communicate using a single relay equipped with N antennas. Both co-channel interference and AWGN are present at the relay and destination. To the best of author's knowledge, there is no existing literature that analyzes the effects of very large antenna arrays on the performance of the considered system. The novelty and key results of this paper can be listed as follows:

- A tight lower bound on the achievable rate of the considered system is derived by taking into account N, K, the number of interferers, the first-hop signal-to-noise ratio (SNR) ρ_1, the second-hop SNR ρ_2 and the interference power.
- We perform a large system analysis for four cases: 1) fixed K and $N \to \infty$; 2) fixed $\alpha = K/N (\alpha < 1)$ and K, $N \to \infty$; 3) fixed N, K and $\rho_1 \to \infty$; 4) fixed N, K and $\rho_2 \to \infty$. It is shown that we cannot improve the AF relaying system performance by simply increasing the SNR ρ_1 or ρ_2. However, increasing the number of relay antennas is an efficient solution to further improve the system performance.

II. System Model

We assume that the source S_k wants to communicate with the destination D_k, for $k = 1, \dots, K$, with the help of a shared relay R, as illustrated in Fig. 1. Each source/destination terminal is equipped with a single antenna while the relay node is equipped with low-gain, omnidirectional array of N

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antennas. Typically, $N \geq K$. The direct link from S_k to D_k is ignored due to obstacles and path loss attenuation. Perfect knowledge of channel state information (CSI) is available. The system model is first proposed in [15]. As an extension, the current work considers a CCI scenario at both the relay and destinations.

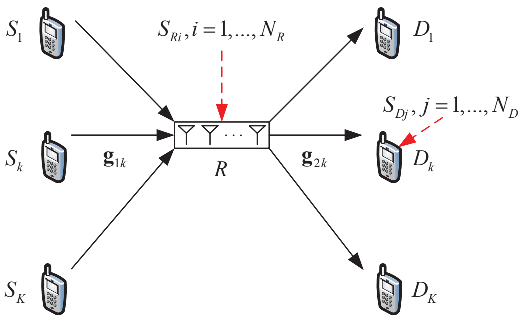

Fig. 1. System model.

Each transmission consists of two phases. In the first phase, all sources simultaneously transmit their signals to the relay, and the received $N \times 1$ vector at the relay is given by

$$\mathbf{y}_r = \sum_{k=1}^{K} \mathbf{g}_{1k} x_k + \sum_{i=1}^{N_R} \mathbf{g}_{Ri} s_{Ri} + \mathbf{n}_1 \tag{1}$$

where N_R is the number of interferers at R, $\mathbf{g}_{1k}$ and $\mathbf{g}_{Ri} = \sqrt{\beta_{Ri}}\mathbf{h}_{Ri}$ denote the channel from S_k and the i-th interferer, respectively. x_k is the information symbol transmitted by S_k satisfying $\mathbb{E}\{|x_k|^2\} = P_s$, s_{Ri} is the i-th interference symbol with $\mathbb{E}\{|s_{Ri}|^2\} = P_{Ri}$, and $\mathbf{n}_1 \sim \mathcal{CN}(0, \sigma_n^2 \mathbf{I})$ represents the AWGN at the relay.

In the second phase, the relay retransmits a transformed version of the received signal to the destination, and the signal at D_k can be expressed as

$$\begin{aligned} y_{D_k} &= \mathbf{g}_{2k}^H \mathbf{W} \mathbf{y}_r + \sum_{j=1}^{N_D} g_{Dj} s_{Dj} + n_{2k} \\ &= \underbrace{\mathbf{g}_{2k}^H \mathbf{W} \mathbf{g}_{1k} x_k}_{\text{desired signal}} + \underbrace{\mathbf{g}_{2k}^H \mathbf{W} \sum_{k' \neq k}^{K} \mathbf{g}_{1k'} x_{k'}}_{\text{multiuser interference}} \\ &\quad + \underbrace{\mathbf{g}_{2k}^H \mathbf{W} \sum_{i=1}^{N_R} \mathbf{g}_{Ri} s_{Ri} + \sum_{j=1}^{N_D} g_{Dj} s_{Dj}}_{\text{co-channel interference}} + \underbrace{\mathbf{g}_{2k}^H \mathbf{W} \mathbf{n}_1 + n_{2k}}_{\text{noise}} \end{aligned} \tag{2}$$

where N_D is the number of interferers at D_k, $\mathbf{g}_{2k}$ and $g_{Dj} = \sqrt{\beta_{Dj}} h_{Dj}$ denote the channel from R and the j-th interferer, respectively. s_{Dj} is the j-th interference symbol with $\mathbb{E}\{|s_{Dj}|^2\} = P_{Dj}$, n_{2k} is the AWGN at D_k with $\mathbb{E}\{|n_{2k}|^2\} = \sigma_n^2$, $\mathbf{W}$ is the $N \times N$ transformation matrix and will be specified in the following section.

We assume that the entries of $\mathbf{g}_{1k}$, $\mathbf{g}_{2k}$, $\mathbf{h}_{Ri}$ and h_{Dj} are independent and identically distributed complex Gaussian random variables with zero mean and unit variance. Moreover, $\beta_{Ri} < 1$ and $\beta_{Dj} < 1$ represent the constant path-loss attenuation and shadow fading from the i-th interferer at R and the j-th interferer at D_k, respectively.

The first term in (2) is the desired signal, while the remaining terms in sequence represent multiuser interference, co-channel interference and noise. As a result, the instantaneous end-to-end signal-to-interference-plus-noise ratio (SINR) experienced at D_k is given by (3) on the top of the next page.

III. Performance Analysis

In this section, we derive an analytical lower bound on the achievable rate of the considered relaying system. We first perform a general analysis for any arbitrary number of relay antennas N. Then we analyze the asymptotic performance in the regimes of high SNR, large N and large K. We will restrict consideration to linear processing because of the low complexity and good performance [5]. Specifically, the relay first performs linear combining method to suppress the multiuser interference and co-channel interference, and then forwards the transformed signal to the destination using linear precoding scheme.

A. General Analysis

We consider the use of zero-forcing (ZF) reception/zero-forcing transmission at the relay. Note that minimum mean square error (MMSE) scheme always performs better than the ZF scheme, but the analysis of MMSE scheme is a more challenging mathematical problem due to the inverse matrix manipulation and also requires additional knowledge of noise and interference statistics, especially in the relay systems. For the ZF case, the transformation matrix can be expressed as

$$\mathbf{W} = a_{\text{zf}} \mathbf{G}_2 \left(\mathbf{G}_2^H \mathbf{G}_2\right)^{-1} \left(\mathbf{G}_1^H \mathbf{G}_1\right)^{-1} \mathbf{G}_1^H \tag{4}$$

where $\mathbf{G}_1 = [\mathbf{g}_{11}, \ldots, \mathbf{g}_{1K}]$ and $\mathbf{G}_2 = [\mathbf{g}_{21}, \ldots, \mathbf{g}_{2K}]$ are the channel matrices for the first-hop and the second-hop, respectively.

In order to satisfy the transmit power constraint of the relay, i.e., $\mathbb{E}\{\|\mathbf{W}\mathbf{y}_r\|^2\} = P_r$, after some basic algebraic manipulations, a_{zf}^2 can be computed as

$$a_{\text{zf}}^2 = \frac{P_r}{\text{Tr}\left\{P_s y_2 + \left(\sum_{i=1}^{N_R} \beta_{Ri} P_{Ri} + \sigma_n^2\right) y_2 y_1\right\}} \tag{5}$$

where $y_l \triangleq \left(\mathbf{G}_l^H \mathbf{G}_l\right)^{-1}$, $l \in \{1, 2\}$. The derivation process of (5) uses the mutual independence assumption of the channels from different interferers.

Note that $\mathbf{g}_{2k}^H \mathbf{W} \mathbf{g}_{1k'} = a_{\text{zf}} \delta_{kk'}$ where $\delta_{kk'} = 1$ when $k = k'$ and 0 otherwise, $\left|\mathbf{g}_{2k}^H \mathbf{W} \mathbf{g}_{Ri}\right|^2 = a_{\text{zf}}^2 \beta_{Ri} y_{1k}$ and $\left\|\mathbf{g}_{2k}^H \mathbf{W}\right\|^2 = a_{\text{zf}}^2 y_{1k}$ where $y_{1k} \triangleq \left[\left(\mathbf{G}_1^H \mathbf{G}_1\right)^{-1}\right]_{kk}$, therefore, the SINR in (3) turns out to be

$$\gamma_k^{\text{zf}} = \frac{a_{\text{zf}}^2 P_s}{a_{\text{zf}}^2 \left(\sum_{i=1}^{N_R} \beta_{Ri} P_{Ri} + \sigma_n^2\right) y_{1k} + \sum_{j=1}^{N_D} \beta_{Dj} P_{Dj} + \sigma_n^2} \tag{6}$$

$$\gamma_k = \frac{\left|\mathbf{g}_{2k}^H \mathbf{W} \mathbf{g}_{1k}\right|^2 P_s}{\sum_{k' \neq k}^{K} \left|\mathbf{g}_{2k}^H \mathbf{W} \mathbf{g}_{1k'}\right|^2 P_s + \sum_{i=1}^{N_R} \left|\mathbf{g}_{2k}^H \mathbf{W} \mathbf{g}_{Ri}\right|^2 P_{Ri} + \sum_{j=1}^{N_D} |g_{Dj}|^2 P_{Dj} + \left\|\mathbf{g}_{2k}^H \mathbf{W}\right\|^2 \sigma_n^2 + \sigma_n^2} \quad (3)$$

For notational convenience, we define $\rho_1 = \frac{P_s}{\sigma_n^2}$, $\rho_2 = \frac{P_r}{\sigma_n^2}$, $\rho_{Ri} = \frac{P_{Ri}}{\sigma_n^2}$, $\rho_{Dj} = \frac{P_{Dj}}{\sigma_n^2}$, $\sum_{i=1}^{N_R} \beta_{Ri}\rho_{Ri} = \rho_R$ and $\sum_{j=1}^{N_D} \beta_{Dj}\rho_{Dj} = \rho_D$, then (5) becomes

$$a_{\text{zf}}^2 = \frac{\rho_2}{\text{Tr}\left\{\rho_1 y_2 + (\rho_R + 1) y_2 y_1\right\}} \quad (7)$$

Substituting (7) into (6), we have

$$\gamma_k^{\text{zf}} = \frac{\rho_1\rho_2}{\rho_2(\rho_R + 1) y_{1k} + (\rho_D + 1)\text{Tr}\left\{\rho_1 y_2 + (\rho_R + 1) y_2 y_1\right\}} \quad (8)$$

With the simplified form of γ_k^{zf} in (8), the expectation of y_{1k}, y_2 and $y_2 y_1$ are also required. According to [16], y_{1k} can be modelled as an inverse Gamma distribution with shape parameter $N - K + 1$ and scale parameter 1. It is easy to observe that

$$\mathbb{E}\left\{y_{1k}\right\} = \frac{1}{N-K} \quad (9)$$

To calculate the trace of y_2 and $y_2 y_1$, we first review the following identities [17, Lemma 2.10]:

$$\mathbb{E}\left\{\text{tr}\left(\mathbf{A}^{-1}\right)\right\} = \frac{m}{n-m} \quad (10)$$

$$\mathbb{E}\left\{\text{tr}\left(\mathbf{A}^{-2}\right)\right\} = \frac{mn}{(n-m)^3 - (n-m)}, \; n \geq m+1 \quad (11)$$

where $\mathbf{A} \sim \mathcal{W}_m(n, \mathbf{I})$ is an $m \times m$ central complex Wishart matrix with n ($n > m$) degrees of freedom. From the definition of y_l, $l \in \{1, 2\}$, it is easy to obtain

$$\mathbb{E}\left\{\text{tr}(y_l)\right\} = \frac{K}{N-K} \quad (12)$$

$$\mathbb{E}\left\{\text{tr}(y_l^2)\right\} = \frac{NK}{(N-K)^3 - (N-K)}, \; N \geq K+1 \quad (13)$$

Invoking the Cauchy-Schwarz's inequality, we have

$$\mathbb{E}\left\{\text{tr}(y_2 y_1)\right\} \leq \mathbb{E}\left\{\left[\text{tr}\left(y_2^2\right)\right]^{1/2}\left[\text{tr}\left(y_1^2\right)\right]^{1/2}\right\} \quad (14)$$

Since y_1 and y_2 are independent random matrices, we obtain

$$\mathbb{E}\left\{\text{tr}(y_2 y_1)\right\} \leq \frac{NK}{(N-K)^3 - (N-K)} \quad (15)$$

Now, we consider the achievable rate of the k-th destination node D_k which is given by

$$R_k^{\text{zf}} = \mathbb{E}\left\{\log_2\left(1 + \gamma_k^{\text{zf}}\right)\right\} \quad (16)$$

From (8), by the convexity of $\log_2(1 + \frac{1}{x})$ and using Jensen's inequality, R_k^{zf} can be further derived as (17).

Combining (17) with (9), (12) and (15), we obtain the following lower bound on the achievable rate:

$$R_k^{\text{zf}} \geq \tilde{R}_k^{\text{zf}} = \log_2\left(1 + \frac{\rho_1\rho_2}{\frac{\rho_2(\rho_R+1)}{N-K} + \frac{\rho_1(\rho_D+1)K}{N-K} + \frac{(\rho_R+1)(\rho_D+1)NK}{(N-K)^3-(N-K)}}\right) \quad (18)$$

If maximum-ratio combining (MRC) is adopted at the relay, the transformation matrix is given by

$$\mathbf{W} = a_{\text{mrc}}\mathbf{G}_2\mathbf{G}_1^H \quad (19)$$

Similarly, considering the relay power constraint and using Eq. (1), after some mathematical calculations, a_{mrc}^2 can be calculated as

$$a_{\text{mrc}}^2 = \frac{P_r}{\text{Tr}\left\{P_s y_1^{-2} y_2^{-1} + \left(\sum_{i=1}^{N_R}\beta_{Ri}P_{Ri} + \sigma_n^2\right)(y_2 y_1)^{-1}\right\}} = \frac{\rho_2}{\text{Tr}\left\{\rho_1 y_1^{-2} y_2^{-1} + (\rho_R + 1)(y_2 y_1)^{-1}\right\}} \quad (20)$$

Here, let $Z_k \triangleq \left[\mathbf{G}_2^H\mathbf{G}_2\mathbf{G}_1^H\mathbf{G}_1\mathbf{G}_2^H\mathbf{G}_2\right]_{kk}$, then we have that $\left|\mathbf{g}_{2k}^H\mathbf{W}\mathbf{g}_{1k'}\right|^2 = a_{\text{mrc}}^2 Z_k$, $\left|\mathbf{g}_{2k}^H\mathbf{W}\mathbf{g}_{Ri}\right|^2 = a_{\text{mrc}}^2\beta_{Ri}Z_k$ and $\left\|\mathbf{g}_{2k}^H\mathbf{W}\right\|^2 = a_{\text{mrc}}^2 Z_k$.

Invoking the SINR in (3), we can obtain the simplified form of γ_k^{mrc} as given by (21) on the top of the next page. As a comparison, (21) will be used to obtain the simulation curves of MRC scheme in Section IV.

B. Asymptotic Analysis

In order to get further insights into the effects of various system parameters on the performance of the system, we perform an asymptotic analysis using the lower bound (18). We have the following key results.

1) For fixed K and $N \to \infty$:

$$\lim_{N\to\infty} \tilde{R}_k = \infty \quad (22)$$

The above result reveals that when the number of relay antennas goes to infinity, the effects of interference and noise disappear. Therefore, by increasing N, the achievable rate grows without limit providing perfect CSI is available at the relay.

2) For fixed $\alpha = K/N (\alpha < 1)$ and K, $N \to \infty$:

$$\lim_{N\to\infty} \tilde{R}_k = \log_2\left(1 + \frac{\rho_2}{\rho_D + 1}\left(\frac{1}{\alpha} - 1\right)\right) \quad (23)$$

The interesting operating regime in practice is that the number of relay antennas is large but may not be much greater than the number of UTs. In this case, the achievable rate depends on the second-hop SNR ρ_2, the interference power ρ_D and the ratio α when N and K go to infinity simultaneously.

3) For fixed N, K and $\rho_1 \to \infty$:

$$\lim_{\rho_1\to\infty} \tilde{R}_k = \log_2\left(1 + \frac{\rho_2}{\rho_D + 1}\frac{N-K}{K}\right) \quad (24)$$

This means that the achievable rate will not reduce as $\rho_1 \to \infty$, but instead floor at a fixed value that is lower bounded by (24). However, the system performance can be further improved by increasing the number of relay antennas.

$$R_k^{\text{zf}} \geq \log_2\left(1+\frac{\rho_1\rho_2}{\mathbb{E}\left\{\rho_2\left(\rho_R+1\right)y_{1k}+(\rho_D+1)\text{Tr}\left\{\rho_1 y_2+\left(\rho_R+1\right)y_2 y_1\right\}\right\}}\right) \tag{17}$$

$$\gamma_k^{\text{mrc}} = \frac{Z_k\rho_1\rho_2}{Z_k\rho_1\rho_2(K-1)+\rho_2\left(\rho_R+1\right)Z_k+(\rho_D+1)\text{Tr}\left\{\rho_1 y_1^{-2}y_2^{-1}+\left(\rho_R+1\right)\left(y_2 y_1\right)^{-1}\right\}} \tag{21}$$

4) For fixed N, K and $\rho_2 \to \infty$:

$$\lim_{\rho_2\to\infty}\tilde{R}_k = \log_2\left(1+\frac{\rho_1}{\rho_R+1}(N-K)\right) \tag{25}$$

For this case, the achievable rate converges to a constant value that is dependent on the first-hop SNR ρ_1 and the interference power ρ_R.

IV. Numerical Results

In this section, some numerical results are provided to validate our analysis and investigate the joint effect of key system parameters on the system performance. The achievable sum rate of the UTs at the destination is $C_{\text{sum}} = \sum_{k=1}^{K} R_k$. In Fig. 2 to Fig. 4, the simulation curves are obtained by using (16), while the analytical bound curves are calculated via (18). In Fig. 5, the simulation curves for MRC scheme come from (21). The simulation parameters are given in the caption of every figure.

Fig. 2 demonstrates the achievable sum rate against the first-hop SNR ρ_1 with different number of relay antennas N. The value of ρ_2 is set to be equal to ρ_1. It can be observed that the lower bound expression derived in (18) is sufficiently tight across the entire SNR range of interest and becomes exact when N is very large. In addition, the number of relay antennas N has a significant impact on the system performance, which can be further confirmed by the observations from Fig. 3 and Fig. 4.

Fig. 3 illustrates the achievable sum rate versus the number of relay antennas N with different SNR and interference power. The value of ρ_2 is set to be constant, i.e., $\rho_2 = 0$ dB. It is clear that increasing ρ_1 yields a significant sum rate improvement, while increasing ρ_{Ri} and ρ_{Dj} deteriorates the performance. This is obviously consistent with our intuitions. We can see that the gap between the curves of different ρ_1 becomes smaller when ρ_1 increases due to the floor effect as discussed in (24). Moreover, from Fig. 3, we can gain some insights into which part of CCI (at the relay or destination) has the dominant effect on the sum rate. Clearly, the answer is the CCI at the destination.

Fig. 4 shows the impact of the number of interferers and path loss on the achievable sum rate. As expected, increasing N_R, N_D, β_{Ri} and β_{Dj} degrades the system performance.

Fig. 5 compares the ZF scheme with the MRC scheme. It is observed that ZF scheme is superior to MRC scheme and affected by the number of relay antennas significantly. However, the MRC scheme converges more quickly to a constant as the SNR increases, and increasing the relay antennas can not increase the sum rate in the regimes of high SNR due to

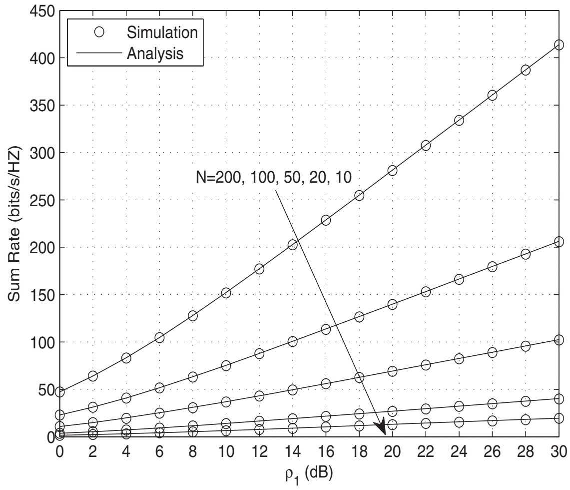

Fig. 2. The achievable sum rate versus SNR ($\alpha = 1/5$, $N_R = N_D = 2$, $\rho_2 = \rho_1$, $\rho_{Ri} = \rho_{Dj} = 0$ dB, $\beta_{Ri} = \beta_{Dj} = 1$, $\forall\, i, j$).

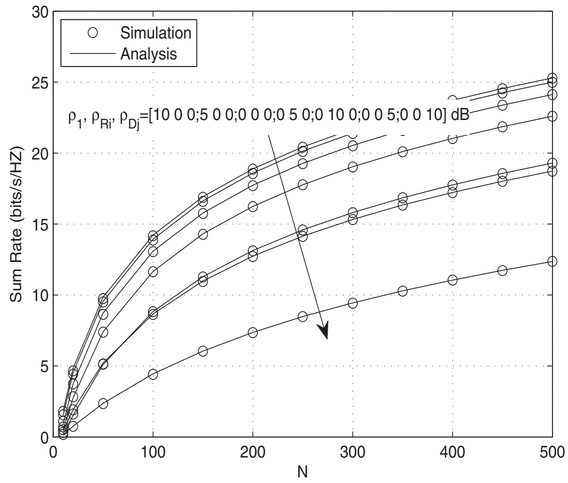

Fig. 3. The achievable sum rate versus N with different ρ_1, ρ_{Ri} and ρ_{Dj} ($K = 5$, $N_R = N_D = 2$, $\rho_2 = 0$ dB, $\beta_{Ri} = \beta_{Dj} = 1$, $\forall\, i, j$).

the factor Z_k in (21), and the multiuser interference is not canceled out if MRC is adopted at the relay.

V. Conclusion

We have investigated the performance of a large-scale MU-MIMO system with AF relaying in the presence of co-channel

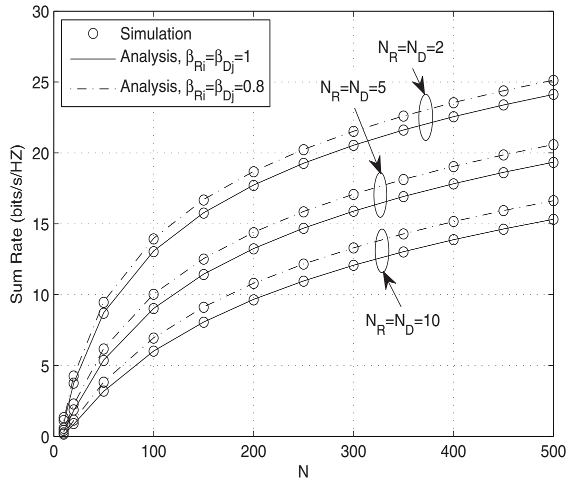

Fig. 4. The achievable sum rate versus N with different number of interferers ($K = 5$, $\rho_1 = \rho_2 = 0$ dB, $\rho_{Ri} = \rho_{Dj} = 0$ dB, $\forall\ i,\ j$).

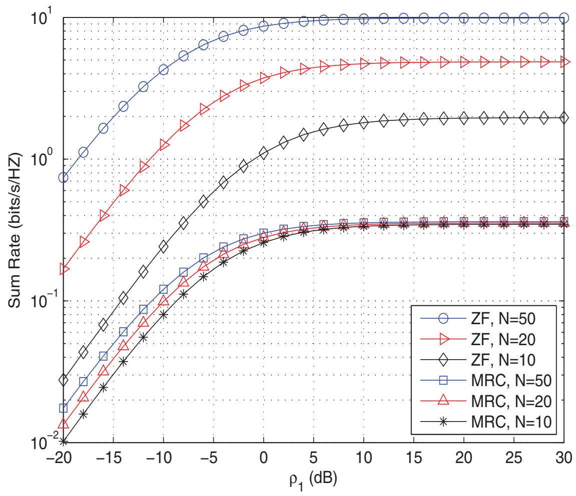

Fig. 5. Comparison of simulation results for ZF and MRC scheme ($K = 5$, $N_R = N_D = 2$, $\rho_2 = 0$ dB, $\rho_{Ri} = \rho_{Dj} = 0$ dB, $\beta_{Ri} = \beta_{Dj} = 1$, $\forall\ i,\ j$).

interference. A sufficient tight analytical bound expression on the achievable rate is derived. A general and an asymptotic analysis are performed respectively, which enable us to assess the impact of various key system parameters, that is, the number of relay antennas, the number of UTs, the number of interferers, the first-hop SNR, the second-hop SNR and the interference power. It is shown that the achievable rate will saturate to a floor by simply increasing the transmitted power of each user or the relay. Notwithstanding, both analytical and simulation results reveal that the system can still be significantly improved by implementing more antennas at the relay.

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References

[1] T. L. Marzetta, “Noncooperative cellular wireless with unlimited numbers of base station antennas,” *IEEE Trans. Wireless Commun.*, vol. 9, no. 11, pp. 3590–3600, Nov. 2010.
[2] F. Rusek, D. Persson, B. K. Lau, E. G. Larsson, T. L. Marzetta, O. Edfors, and F. Tufvesson, “Scaling up MIMO: Opportunities and challenges with very large arrays,” *IEEE Signal Process. Mag.*, vol. 30, no. 1, pp. 40–60, Jan. 2013.
[3] E. G. Larsson, O. Edfors, F. Tufvesson, and T. L. Marzetta, “Massive MIMO for next generation wireless systems,” *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 186–195, Feb. 2014.
[4] J. Hoydis, S. ten Brink, and M. Debbah, “Massive MIMO in the UL/DL of cellular networks: How many antennas do we need?” *IEEE J. Sel. Areas in Commun.*, vol. 31, no. 2, pp. 160–171, Feb. 2013.
[5] H. Q. Ngo, E. G. Larsson, and T. L. Marzetta, “Energy and spectral efficiency of very large multiuser MIMO systems,” *IEEE Trans. Commun.*, vol. 61, no. 4, pp. 1436–1449, Apr. 2013.
[6] M. Liu, J. Zhang, and P. Zhang, “Outage probability of dual-hop multiple antenna relay systems with interference at the relay and destination,” *International Journal of Antennas and Propagation*, vol. 2014, pp. 1–7, Oct. 2014, http://dx.doi.org/10.1155/2014/370684.
[7] ——, “Multipair two-way relay networks with very large antenna arrays,” in *Proc. IEEE Vehicular Technology Conference (VTC)*, Vancouver, Canada, Sept. 2014, pp. 1–5.
[8] W. Xu, J. Zhang, and P. Zhang, “Outage probability of two-hop fixed-gain relay with interference at the relay and destination,” *IEEE Commun. Lett.*, vol. 15, no. 6, pp. 608–610, Jun. 2011.
[9] M. Xia and S. Aissa, “Impact of co-channel interference on the performance of multi-hop relaying over Nakagami-m fading channels,” *IEEE Wireless Commun. Lett.*, vol. 3, no. 2, pp. 133–136, Apr. 2014.
[10] H. Q. Ngo, H. A. Suraweera, M. Matthaiou, and E. G. Larsson, “Multipair full-duplex relaying with massive arrays and linear processing,” *IEEE J. Sel. Areas in Commun.*, vol. 32, no. 9, pp. 1721–1737, Sept. 2014.
[11] 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.
[12] G. Zhu, C. Zhong, H. A. Suraweera, Z. Zhang, and C. Yuen, “Outage probability of dual-hop multiple antenna AF systems with linear processing in the presence of co-channel interference,” *IEEE Trans. Wireless Commun.*, vol. 13, no. 4, pp. 2308–2321, Apr. 2014.
[13] K. S. Karthik and B. Ramamurthi, “A two-hop AF relaying scheme with interference suppression at the relay,” *IEEE Trans. Vehicular Technology,*, vol. 63, no. 7, pp. 3469–3474, Sept. 2014.
[14] H. Q. Ngo and E. G. Larsson, “Large-scale multipair two-way relay networks with distributed AF beamforming,” *IEEE Commun. Lett.*, vol. 17, no. 12, pp. 1–4, Dec. 2013.
[15] 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 International Conference on Communications (ICC)*, Budapest, Hungary, Jun. 2013, pp. 4635–4640.
[16] P. Li, D. Paul, R. Narasimhan, and J. Cioffi, “On the distribution of SINR for the MMSE MIMO receiver and performance analysis,” *IEEE Trans. Inf. Theory*, vol. 52, no. 1, pp. 271–286, Jan. 2006.
[17] A. M. Tulino and S. Verdú, *Random Matrix Theory and Wireless Communications*. Hanover, MA: Now Publishers Inc., 2004.