Massive MIMO System: An Overview

Muaayed AL-Rawi

Abstract—**This paper studies the performance of massive MIMO uplink system over Rician fading channel. The performance is measured in terms of spectral efficiency versus number of base station antennas using three schemes of linear detection, maximum-ratio-combining(MRC), zero forcing receiver(ZF), and minimum mean-square error receiver(MMSE). The simulation results show that the spectral efficiency increases significantly with increasing the number of base station antennas. Also, the spectral efficiency with MMSE is better than that with ZF, and the latter is better than that with MRC. In addition, the spectral efficiency decreases with increasing the fading parameter.**

Keywords— **Massive MIMO; Rician fading channel**

I. Introduction

Multiple Input Multiple Output (MIMO) technology is a point-to-point communication links with multiple antennas at both the transmitter and receiver. The use of multiple antennas at both transmitter and receiver clearly provide an improvements on *data rate*, because the more antennas, the more independent data streams can be sent out; an improvements on *reliability*, because the more antennas, the more possible paths that the radio signal can propagate over, and an improvements on *energy efficiency*, because the base station can focus its emitted energy into the spatial directions where it knows that the terminals are located.

An enhanced form of point-to-point MIMO technology is multiuser MIMO (MU-MIMO) which enables multiple independent radio terminals to access a system enhancing the communication capabilities of each individual terminal. MU-MIMO differs from point-to-point MIMO in two respects: first, the terminals are typically separated by many wavelengths, and second, the terminals cannot collaborate among themselves, either to transmit or to receive data.

Nowadays, MU-MIMO systems are used in a new generation wireless technologies. Due to that wireless technology improvement is ongoing, the numbers of users and applications increase rapidly. Then, wireless communications need the high data rate and link reliability at the same time. Therefore, MU-MIMO improvements have to consider 1) providing the high data rate and link reliability, 2) support all users in the same time and frequency resource, and 3) using low power consumption. In practice, the interuser interference has a strong impact when more users access to the wireless link. Complicated transmission techniques such as interference cancellation should be used to maintain a given desired quality of service. Due to these problems, MU-MIMO with very large antenna arrays (known as massive MIMO) are proposed[1-9]. With a massive MU-MIMO system, we mean a hundred of antennas or more serving tens of users. The channel vectors are nearly orthogonal, and then the interuser interference is reduced significantly. Therefore, the users can be served with high data rate simultaneously.

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II. System Model

The model of massive MIMO system considered here consists of uplink system model, channel model(Rician fading channel), and linear detection schemes. These three parts are discussed in details in the next sections.

A. *Uplink System Model*

A single-cell uplink system is considered here, where there are K mobile users and one base station (BS). Each user has one transmit antenna, and the BS has M receive antennas as shown in Fig.1. The received signal at the BS is

$$\boldsymbol{y} = \sqrt{p_u}\sum_{k=1}^{K} \boldsymbol{h}_k x_k + \boldsymbol{n} \tag{1}$$

$$\boldsymbol{y} = \sqrt{p_u}\boldsymbol{H}\boldsymbol{x} + \boldsymbol{n} \tag{2}$$

where $\sqrt{p_u}x_k$ is the transmitted signal from the kth user (the average power transmitted by each user is p_u), $\boldsymbol{h}_k \in \mathbb{C}^{M\times 1}$is the channel vector between the kth user and the BS, $\boldsymbol{n} \in \mathbb{C}^{M\times 1}$ is the additive noise vector, $\boldsymbol{H} \triangleq [\boldsymbol{h}_1 \quad \dots \quad \boldsymbol{h}_K]$ is channel matrix given below, and $\boldsymbol{x} \triangleq [x_1 \quad \dots \quad x_K]^T$. It is assumed that the elements of $\boldsymbol{h}_k$ and $\boldsymbol{n}$ are (independent identically distribution) i.i.d. Gaussian distributed with zero mean and unit variance.

$$\boldsymbol{H} = \begin{bmatrix} h_{11} & h_{12} & \dots & h_{1K} \\ h_{21} & h_{22} & \dots & h_{2K} \\ \vdots & \vdots & \ddots & \vdots \\ h_{M1} & h_{M2} & \dots & h_{MK} \end{bmatrix} \tag{3}$$

The BS will coherently detect the signals transmitted from K users by using the received signal vector $\boldsymbol{y}$ together with knowledge of the channel state information (CSI). This CSI has to be estimated. The channel estimate can be obtained from uplink training.

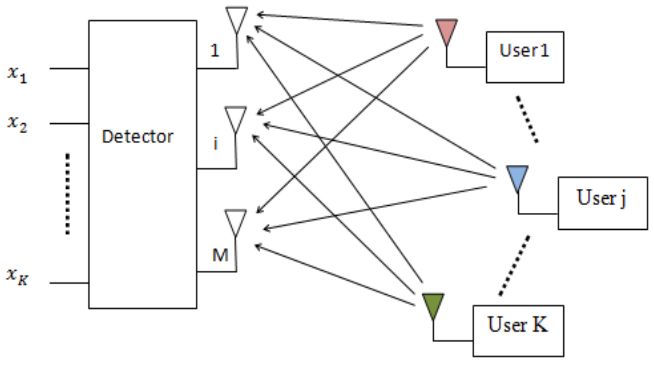

Fig.1 Massive MIMO uplink system model

It is assumed that the channel stays constant over T symbol durations. During each coherence interval, there are two phases (see Fig.2). In the first phase, a part τ of the coherence interval is used for uplink training to estimate the channel of each user. In the second phase, all K users simultaneously transmit their data to the BS. The BS then detects the transmitted signals using the channel estimates acquired in the first phase.

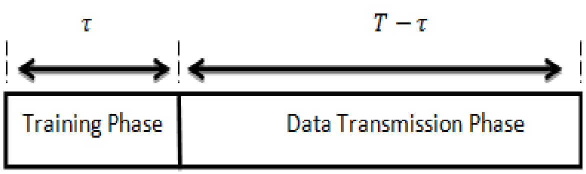

Fig.2 Uplink transmission protocol

B. *Rician Fading Channel*

A probability density function of the signal received in the line-of-sight(LOS) environment follows the Rician distribution. In the LOS environment where there exists a strong path which is not subject to any loss due to reflection, diffraction, and scattering, the amplitude of the received signal can be expressed as $X = a + W1 + jW2$ where a represents the LOS component, while, $W1$ and $W2$ are the i.i.d. Gaussian random variables with a zero mean and variance of σ^2 as in the non-LOS environment. It has been known that X is the Rician random variable. Then, the channel coefficient of Rician fading channel is given by

$$h_{Rician} = a + c + jd \qquad (4)$$

where $a = \sqrt{\frac{\mathcal{K}}{\mathcal{K}+1}}$, $c \sim \mathcal{N}\left(0, \frac{1}{2(\mathcal{K}+1)}\right)$, $d \sim \mathcal{N}\left(0, \frac{1}{2(\mathcal{K}+1)}\right)$, and $\mathcal{K}$ is the ratio of the power in the LOS component to the power in the other (non-LOS) multipath components.

The fading parameter $\mathcal{K}$ which is usually given in dB is a measure of the severity of the fading, a small $\mathcal{K}$ implies severe fading, while, a large $\mathcal{K}$ implies milder fading.

C. *Linear Detection*

To obtain optimal performance, the maximum likelihood(ML) multiuser detection can be used by the BS to detect all signals transmitted from *k* user, assuming that the BS has perfect CSI knowledge. The complexity of ML is high, so the BS can use linear detection schemes to reduce the decoding complexity. However, these schemes have lower detection reliability compared with ML detection but when the number of BS antennas is large, linear detectors are nearly-optimal. Three schemes of linear detection are considered, maximum-ratio combining(MRC), zero-forcing receiver(ZF), and minimum mean-square error receiver(MMSE) as described below.

1-Maximum-Ratio Combining(MRC)

With MRC, the BS maximizes the received signal-to-noise ratio (SNR) of each stream, ignoring the effect of multiuser interference. As a result, to detect the transmitted signal from the *k*-th user, the received signal $\boldsymbol{y}$ is multiplied by the conjugate-transpose of the channel vector $\boldsymbol{h}_k$, as follows

$$\tilde{y}_k = \boldsymbol{h}_k{}^H \boldsymbol{y} = \sqrt{p_u}\|\boldsymbol{h}_k\|^2 x_k + \sqrt{p_u}\sum_{i\neq k}^{K} \boldsymbol{h}_k{}^H \boldsymbol{h}_i x_i + \boldsymbol{h}_k{}^H \boldsymbol{n} \qquad (5)$$

The received signal-to-interference-plus-noise ratio (SINR) of the *k*th stream for MRC is given by

$$SINR_{mrc,k} = \frac{p_u \|\boldsymbol{h}_k\|^4}{p_u \sum_{i\neq k}^{K} \left|\boldsymbol{h}_k{}^H \boldsymbol{h}_i\right|^2 + \|\boldsymbol{h}_k\|^2} \qquad (6)$$

The achievable rate of *k*th user with MRC is given by

$$\boldsymbol{R}_k{}^{MRC} = log_2\left(1 + \frac{p_u \|\boldsymbol{h}_k\|^4}{p_u \sum_{i\neq k}^{K} \left|\boldsymbol{h}_k{}^H \boldsymbol{h}_i\right|^2 + \|\boldsymbol{h}_k\|^2}\right) \qquad (7)$$

Hence the spectral efficiency with MRC is given by

$$\boldsymbol{R}^{MRC} = K * \boldsymbol{R}_k{}^{MRC} = K * log_2\left(1 + \frac{p_u \|\boldsymbol{h}_k\|^4}{p_u \sum_{i\neq k}^{K} \left|\boldsymbol{h}_k{}^H \boldsymbol{h}_i\right|^2 + \|\boldsymbol{h}_k\|^2}\right) \qquad (8)$$

MRC is a very simple signal processing since the BS just multiplies the received vector with the conjugate-transpose of the channel matrix $\boldsymbol{H}$, and then detects each stream separately. More importantly, MRC can be implemented in a distributed manner. In addition, MRC can achieve the same array gain as in the case of a single-user system at low SNR, but MRC performs poorly in interference-limited scenarios because it neglects the effect of multiuser interference.

2- Zero-Forcing Receiver(ZF)

In contrast to MRC, zero-forcing receivers(ZF) take the interuser interference into account, but neglect the effect of noise. With ZF, the multiuser interference is completely nulled out by projecting each stream onto the orthogonal space of the interuser interference. More precisely, the received vector is multiplied by the pseudo-inverse of the channel matrix $\boldsymbol{H}$ as

$$\tilde{\boldsymbol{y}} = (\boldsymbol{H}^H \boldsymbol{H})^{-1}\boldsymbol{H}^H \boldsymbol{y} = \sqrt{p_u}\boldsymbol{x} + (\boldsymbol{H}^H \boldsymbol{H})^{-1}\boldsymbol{H}^H \boldsymbol{n} \quad (9)$$

The received SINR of the kth stream is given by

$$SINR_{zf,k} = \frac{p_u}{[(\boldsymbol{H}^H \boldsymbol{H})^{-1}]_{kk}} \quad (10)$$

The achievable rate of kth user with ZF is given by

$$\boldsymbol{R}_k{}^{ZF} = log_2\left(1 + \frac{p_u}{[(\boldsymbol{H}^H \boldsymbol{H})^{-1}]_{kk}}\right) \quad (11)$$

Hence the spectral efficiency with ZF is given by

$$\boldsymbol{R}^{ZF} = K * \boldsymbol{R}_k{}^{ZF} = K * log_2\left(1 + \frac{p_u}{\left[(\boldsymbol{H}^H \boldsymbol{H})^{-1}\right]_{kk}}\right) \quad (12)$$

ZF is a simple signal processing and works well in interference-limited scenarios, but since ZF neglects the effect of noise, it works poorly under noise-limited scenarios. Compared with MRC, ZF has a higher implementation complexity due to the computation of the pseudo-inverse of the channel gain matrix.

3- Minimum Mean-Square Error Receiver(MMSE)

It is known that the MMSE receiver maximizes the received SINR. Therefore, among the MMSE, ZF, and MRC receivers, MMSE is the best, the received SINR for the MMSE receiver is given by

$$SINR_{mmse,k} = p_u \boldsymbol{h}_k{}^H \left(p_u \sum_{i \neq k}^{K} \boldsymbol{h}_i \boldsymbol{h}_i{}^H + \boldsymbol{I}_M\right)^{-1} \boldsymbol{h}_k \quad (13)$$

The achievable rate of kth user with MMSE is given by

$$\boldsymbol{R}_k{}^{MMSE} = log_2\left(1 + p_u \boldsymbol{h}_k{}^H \left(p_u \sum_{i \neq k}^{K} \boldsymbol{h}_i \boldsymbol{h}_i{}^H + \boldsymbol{I}_M\right)^{-1} \boldsymbol{h}_k\right) \quad (14)$$

Hence the spectral efficiency with MMSE is given by

$$\boldsymbol{R}^{MMSE} = K * \boldsymbol{R}_k{}^{MMSE} = K * log_2\left(1 + p_u \boldsymbol{h}_k{}^H \left(p_u \sum_{i \neq k}^{K} \boldsymbol{h}_i \boldsymbol{h}_i{}^H + \boldsymbol{I}_M\right)^{-1} \boldsymbol{h}_k\right) \quad (15)$$

Where $\boldsymbol{I}_M$ is the identity matrix of size M

III. SIMULATION RESULTS

A series of computer simulation tests are carried out to study the system performance. The performance is measured by drawing the spectral efficiency versus the number of BS antennas using MRC, ZF, and MMSE. The number of users is chosen to be K = 2 and $\mathcal{K} = 0$dB& -40dB. Furthermore, the SNR is set at 0 dB. Fig.3 and Fig.4 show that the spectral efficiency increases as the number of BS antennas increases for $\mathcal{K} = 0$dB&-40dB respectively. Also, the spectral efficiency with MMES is better than that with ZF, and the latter is better than that with MRC for $\mathcal{K} = 0$dB&-40dB. Furthermore, by comparing between Fig.3 and Fig.4, it can concluded that the spectral efficiency for $\mathcal{K} = -40$dB is better than the spectral efficency for $\mathcal{K} = 0$dB.

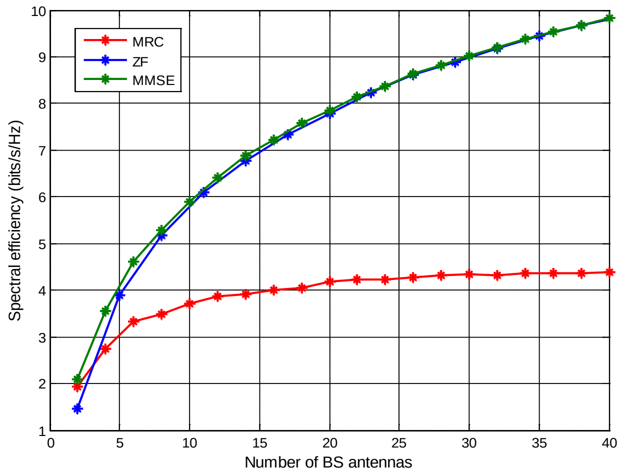

Fig.3 The spectral efficiency versus the number of BS antennas for MRC, ZF, MMSE, and $\mathcal{K} = 0$dB

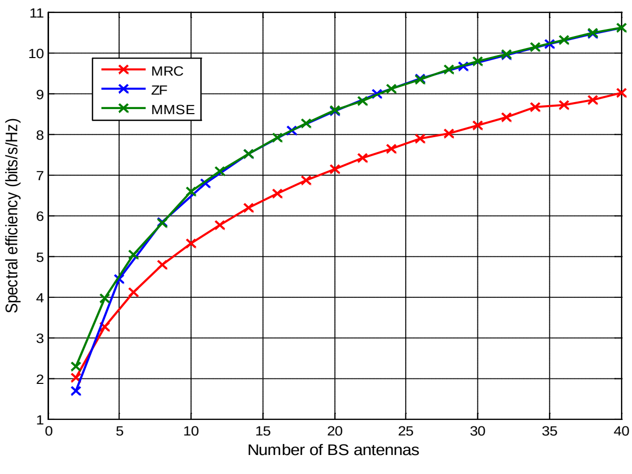

Fig.4 The spectral efficiency versus the number of BS antennas for MRC, ZF, MMSE and $\mathcal{K} = -40$dB

IV. CONCLUSION

The performance of massive MIMO uplink system was measured over Rician fading channel, using MRC, ZF, and MMSE linear detection schemes. The results show that the performance improved significantly with increasing the number of BS antennas for different values of $\mathcal{K}$. Also, the performance with MMSE is better than that with ZF and the latter is better than that with MRC for different values of $\mathcal{K}$. Furthermore, as $\mathcal{K}$ increases, the spectral efficiency decreases.

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