Spectral Efficiency of MU-Massive MIMO System for Perfect and Imperfect CSI Condition

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Abstract— **Multi User Massive MIMO (MU-Massive MIMO) is a form of multi-user large-scale antennas technology, in which hundreds numbers of antennas serve a significantly smaller number of users. We focus to analyze the downlink system of MU-Massive MIMO which works on Rayleigh and Uniformly Random Line of Sight (UR-LOS) channels. This system is assumed operates over a frequency-selective and uses Orthogonal Frequency Division Multiplexing (OFDM). The system performance is observed under perfect CSI and imperfect CSI conditions. Channel estimation for imperfect CSI can be obtained from uplink pilots training. ZF and MMSE linier precoding are used to overcome Multi User Interference (MUI) at receiver. From the simulation results, it can be seen that imperfect CSI has an impact on system performance due to channel estimation errors. In imperfect CSI condition, Bit error rate (BER) of the system is little bit higher and the spectral efficiency is slightly decreased. Furthermore, the use of a large number of array antennas can significantly increase the spectral efficiency without bound, both in perfect and imperfect CSI condition. In addition, spectral efficiency of the downlink scheme really depends on the use of precoding techniques. ZF and MMSE work equally well in suppressing the MUI at large number of antenna elements.**

Keywords— MU-Massive MIMO, Rayleigh, UR-LOS, Perfect CSI, Imperfect CSI, Spectral Efficiency, ZF, MMSE, MUI.

I. INTRODUCTION

In recent years, Multiple Input Multiple Output (MIMO) technology has been developed to support the development of high-speed wireless communication system. This technology has better performance than Single Input Single Output (SISO). This concept becomes the background for the development of Massive MIMO system. Massive MIMO system is a system that uses a very large number of antennas on the BS, the antennas can be hundreds or even more [1]. By using massive antenna elements, the spectral efficiency and energy efficiency will be significantly increased, compared to the small-scale MIMO system.

In order to serve multiple users simultaneously, Multi User Massive MIMO (MU-Massive MIMO) system is used. Hundreds of antennas on a BS can serve tens of users at same time and frequency resources, where each user uses ~~a~~ single antenna. The advantages of single antenna user are that it is inexpensive, simple and uses more efficient power, but each user still get a high throughput [1]. The design and analysis of the Massive MIMO system is an interesting topic to study [2]-[5]. Some advantages of Massive MIMO system compared to conventional MIMO are, only BS that needs to estimate the channel, the number of BS antennas is much larger than the number of users, and simple linear processing techniques can be applied both on the uplink and downlink side [6]. In order to implement MU-Massive MIMO system which represents the real conditions, Channel State Information (CSI) on the BS or user side is required. CSI is not only useful for obtaining high SNR on the user side, but also reducing interference generated by other users in a cell. However, channel estimation will be very complex because it is proportional to the large number of BS antennas, hence some previous research on Massive MIMO system assumed perfect CSI condition on both the BS and the user side [7]-[9]. In actual condition, the channel response can change at any time according to the propagation environment, hence the channel estimation is needed. Imperfection of the channel estimation process due to channel estimation error is known as imperfect CSI condition, because BS only know the noisy version of the channel.

We assume that the system works on TDD operation, so that the uplink and downlink channel are reciprocal. BS can obtain CSI from the uplink pilots training sent by users. The number of transmitted pilots is proportional to the number of users which is much smaller than the number of BS antennas. Then BS use CSI to precode the transmitted signal in order to reduce Multi User Interference (MUI). In addition, the downlink SE for the k-th user in a cell really depends on the precoding capability to reduce interference between users [10]. Form [1,12], it is shown that the use of large-scale antennas on the BS will increase spectral efficiency without bound. Hence, the use of a massive number of antenna elements with constant number of users will significantly increase the spectral efficiency.

This paper analyses single cell MU-Massive MIMO communication system with a downlink scheme on the Rayleigh and the Uniformly Random Line of Sight (UR-LOS) channel. This system is assumed to be operated over a frequency-selective channel and uses Orthogonal Frequency Division Multiplexing (OFDM). We investigated the performance in specific conditions. First, we assume that the BS knows the channel information state (perfect CSI condition). And second, BS estimates the channel at a certain coherence interval (Imperfect CSI condition) using Least-Square (LS) estimation. The parameters that will be observed are Bit Error Rate (BER) and Spectral Efficiency (SE) using Zero Forcing (ZF) and Minimum Mean Square Error (MMSE) linear precoding technique .

Notations: Uppercase and lowercase bold letters denote matrices and vectors. $\mathbb{E}\{.\}$ denotes expectation operator. For a matrix $\mathbf{A}$, we denote the superscripts $(.)^T$, $(.)^H$ as transpose, and Hermitian matrix operation, respectively. While $\mathrm{tr}(\mathbf{A})$ is trace of matrix $\mathbf{A}$ and $\mathbf{I}_K$ is $(K \times K)$ identity matrix. The entries of k-th row and m-th column of matrix $\mathbf{A}$ is denoted by $[\boldsymbol{A}]_{k,m}$. $\mathbb{C}$ represents complex number, while $\mathcal{CN}$ represents complex normal random variable. The accent $|.|$ denote magnitude of a complex number.

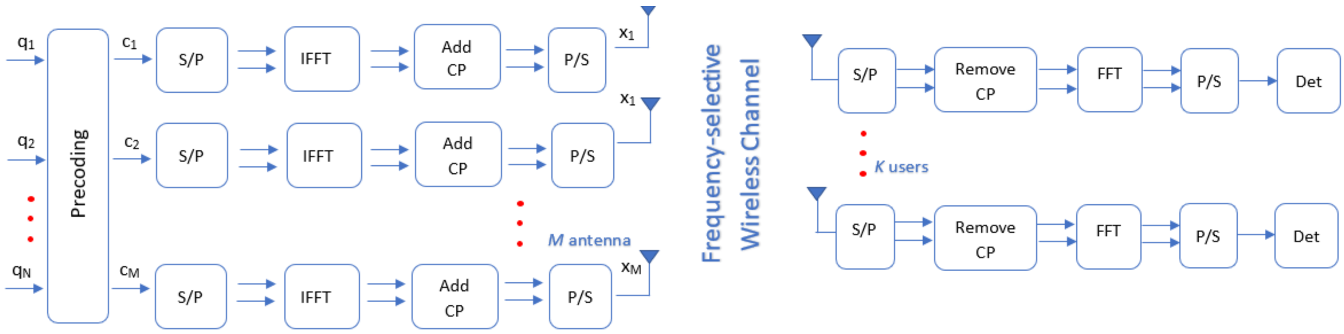

Fig. 1 System model of MU-Massive MIMO downlink scheme.

II. System Model

The downlink system of single cell MU-Massive MIMO is shown in Fig. 1. This system is assumed work on a frequency-selective channel, therefore OFDM technique is used to overcome Inter-symbol Interference (ISI). BS is equipped with M number of antennas,. and simultaneously serves K number of users, each user uses a single antenna, where M is much larger than K. The total number of OFDM subcarriers is denoted by N where N consists of subcarriers designed for data transmission (N_d) and subcarriers for guard band (N_g) in order to reduce out-of-band radiation. Signal vector $q_n \in \mathbb{C}^{M\times 1}$ contains QAM modulated symbols at n-th subcarrier for $n \in N_d$, and no signal transmitted at guard band $q_n \in 0^{M\times 1}$ for $n \in N_g$.

In perfect CSI condition, we assumed that BS already knows the CSI and uses it to precode the transmitted signal. We focus on analyzing the system performance under Rayleigh and UR-LOS channel. The first channel considered is Rayleigh channel where there is no direct line of sight path. The matrix $\mathbf{H}_l \in \mathbb{C}^{K\times M}$ is a time-domain channel response in Rayleigh channel associated with L number of channel taps, where $l = 1, 2, \ldots L$. This matrix contains complex normal random variables $[\mathbf{H}_l]_{k,m} \sim \mathcal{CN}(0, 1/L)$. The second channel condition considered is UR-LOS where there is no local scatterer between BS and users. And all users are in line of sight to the BS antennas. The UR-LOS time domain channel response is described below [10]:

$$\mathbf{h}_k = \sqrt{\beta}\left[1 \quad e^{2\pi j d_H \sin\theta_k} . \; . \; . e^{2\pi j dH(M-1)\sin\theta_k}\right]^T \tag{1}$$

Here h_k is channel response associated with k-th user, β is large-scale fading coefficient, d_H is array spacing and θ_k is angular position of each user which is measured relative to array boresight. BS will only transmit the precoded signal at the specified angle of users. User position is random and $sin(\theta_k)$ is uniformly distributed at interval $[-1,1]$. BS uses Uniform Linear Array (ULA) antennas. Where ULA can only detect the user position uniquely at intervals $[{}^{-\pi}/_2, {}^{\pi}/_2]$.

Channel matrix is assumed to be constant at certain coherence interval. In the imperfect CSI condition, BS needs to estimate the channel response. The channel estimation can be obtained from the training pilots which are transmitted by all users. At each coherence interval, each user transmits orthogonal pilot sequences at length τ_p. The number of transmitted pilots must be greater than the number of users ($\tau_p \geq K$). Collectively, all users transmit $K \times \tau_p$ pilots. This pilot signal is transmitted using N numbers of subcarriers within the coherence interval. The received pilot signal at n-th subcarrier is decribed as [11]:

$$\mathbf{y}_{pn} = \mathbf{H}_n \mathbf{x}_{pn} + \mathbf{w}_n \tag{2}$$

Where $\mathbf{y}_{pn}$ is received pilot signal, $\mathbf{x}_{pn}$ is transmitted pilot signal, $\mathbf{H}_n$ is channel response to be estimated and $\mathbf{w}_n$ is AWGN noise. In order to estimate the channel response, BS needs to know the pilot sequences that transmitted by users, this is why the pilot sequences are deterministic and known at both ends of the link [6,10]. BS will estimate the channel from received pilot signal using LS estimation method. The estimated channel matrix at n-th subcarrier ($\widehat{\mathbf{H}}_n$) can be written as [11]:

$$\widehat{\mathbf{H}}_n = \frac{\boldsymbol{y}_{pn}}{\boldsymbol{x}_{pn}} \tag{3}$$

The channel estimation error can be calculeted as $\widetilde{\mathbf{H}}_n = \widehat{\mathbf{H}}_n - \mathbf{H}_n$. We can calculate the Mean Square Error (MSE) of the channel estimation using $\mathbb{E}\{|\widetilde{\mathbf{H}}_n|^2\}$. After BS knows channel information, then BS will use this channel matrix to precode the transmited signals. There are several simple linear precoding techniques which have low computational complexity and nearly optimal to use since the number of BS antennas is large. In this paper we use ZF and MMSE linier precoding technique and described as follows [8]:

$$\mathbf{A}_n^{ZF} = \mathbf{H}_n^{\mathrm{H}}(\mathbf{H}_n\mathbf{H}_n^{\mathrm{H}})^{-1} \tag{4}$$

$$\mathbf{A}_{\mathbf{n}}^{\mathbf{MMSE}} = \mathbf{H}_{\mathrm{n}}^{\mathrm{H}}\left(\mathbf{H}_{\mathrm{n}}\mathbf{H}_{\mathrm{n}}^{\mathrm{H}} + \frac{K}{p_d}\mathbf{I}_{\mathrm{K}}\right)^{-1} \tag{5}$$

Where $\mathbf{A}_n$ is precoding matrix for n-th subcarrier, and p_d is downlink SNR. To satisfied the total transmit power constraint on the BS, precoding matrix should be multiplied by a scale factor as written in (6)[9].

$$\alpha = \frac{1}{\sqrt{\sum_{n=0}^{N-1} \mathrm{tr}\,(\mathbf{A}\mathbf{A}^{\mathrm{H}})/\mathrm{N}}} \tag{6}$$

Next, the symbols at each subcarrier q_n are multiplied by each subcarrier precoding matrix $\mathbf{A}_n$ and resulting frequency-domain precoded vector $c_m \in \mathbb{C}^{M\times 1}$ which contains the symbols that will be transmitted over n-th subcarrier via M BS antennas. Hence, each BS antenna transmits the signal from all subcarriers. Time-domain signal

x_m is obtained by performing an Inverse Discerete Fourier transform (IDFT) of c_m. Cyclic prefix is inserted to the time-domain signals in order to overcome ISI between OFDM symbols. After passing the wireless channel, all users receive time-domain baseband signal at discrete-time t which in represented in (7):

$$\mathbf{y}_t = \sum_{l=0}^{L-1} \mathbf{H}_l \mathbf{x}_{t-l} + \mathbf{w}_t, \qquad t = 0, 1, \ldots, T-1 \tag{7}$$

Where $\mathbf{y}_t \mathbb{C}^K$ is received baseband vector at time sample t for all users, $\mathbf{H}_l$ is time-domain channel response, $\mathbf{x}_t$ is transmitted signal at time sample t and $\mathbf{w}_t \in \mathcal{CN}(0, N_0 \mathbf{I}_K)$ is Additive White Gaussian Noise (AWGN) at time sample t. Here N_0 is noise power spectral density (PSD) and $\mathbf{I}_K$ is $K \times K$ identity matrix. Then, cyclic prefix is removed from the time-domain received signal.

Furthermore, the received signal at K users as in (7) can be expressed as a matrix, hence $\mathbf{X} = [x_0, x_1, \ldots, x_{T-1}] \in \mathbb{C}^{M \times T}, \mathbf{Y} = [y_0, y_1, \ldots, y_{T-1}] \in \mathbb{C}^{M \times T}$ and $\mathbf{W} \in \mathcal{CN}(0, N_0 \mathbf{I}_K)$ are transmitted signals, received signals and AWGN noises expressed in the time-domain. Then, $\widehat{\mathbf{X}} = \mathbf{X}\mathbf{F}^T$, $\widehat{\mathbf{Y}} = \mathbf{Y}\mathbf{F}^T$ and $\widehat{\mathbf{W}} = \mathbf{W}\mathbf{F}^T$ are frequency domain matrix. Where $\mathbf{F}$ is $N \times N$ DFT matrix as written ini (8).

$$\mathbf{F} = \begin{bmatrix} \mathbf{1} & \mathbf{1} & \cdots & \mathbf{1} \\ \mathbf{1} & \boldsymbol{e^{-j2\pi/N}} & \cdots & \boldsymbol{e^{-j2\pi(N-1)/N}} \\ \vdots & \vdots & \vdots & \vdots \\ \mathbf{1} & \boldsymbol{e^{-j2\pi(N-1)/N}} & \cdots & \boldsymbol{e^{-j2\pi(N-1)(N-1)/N}} \end{bmatrix} \tag{8}$$

The $K \times M$ frequency-domain channel matrix at n-th subcarrier is described as [9]:

$$\widehat{\mathbf{H}}_\mathrm{n} = \sum_{l=0}^{L} \exp\left(-jn \frac{2\pi}{N} l\right) \tag{9}$$

Hence, frequency-domain received signal at n-th subcarrier can be written as [9]:

$$\widehat{\boldsymbol{y}}_n = \widehat{\mathbf{H}}_n \widehat{\mathbf{x}}_n + \mathbf{w}_n \tag{10}$$

Where $\widehat{\mathbf{x}}_n$ and $\widehat{\mathbf{y}}_n$ are the n-th coloum of $\widehat{\mathbf{X}}$ and $\widehat{\mathbf{Y}}$. Morover, the received signal on n-th subcarrier and at k-th user is described as follow:

$$\widehat{\mathbf{y}}_{k,n} = \left[\widehat{\mathbf{H}}_n \mathbf{A}_n\right]_{k,k} \mathbf{q}_{k,n} + \sum_{\substack{v=1 \\ v \neq k}}^{K} \left[\widehat{\mathbf{H}}_n \mathbf{A}_n\right]_{k,v} \mathbf{q}_{v,n} + \mathbf{w}_{k,n} \tag{11}$$

Here, $\mathbf{A} \in \{\mathrm{ZF}, \mathrm{MMSE}\}$, $\mathbf{q}_{k,n}$ is symbol to be transmitted over n-th subcarrier for k-th user, while $\mathbf{q}_{v,n}$ is symbol to be transmitted over n-th subcarrier for all user except k-th user, and $\mathbf{w}_{\mathrm{k,n}}$ is AWGN on n-th subcarrier at k-th user. The first term on the right-hand side of (11) stands for desired signal of k-th user, the second term represents multi user interference, and the third term is AWGN. We assumed that there is only intracell interference and no intercell interference. By using (11) and signal vector $\mathbf{q}_{k,n}$ is assumed to be zero, then signal to Interference Noise Ratio (SINR) at k-th user over n-th subcarrier is defined below [1]:

$$\mathrm{SINR}_{k,n}^{A} = \frac{\left[\left|\widehat{\mathbf{H}}_n \mathbf{A}_n\right|^2\right]_{k,k}}{\sum_{\substack{v=1 \\ v \neq k}}^{K} \left[\widehat{\mathbf{H}}_n \mathbf{A}_n\right]_{k,v} + \mathbf{w}_{kn}} \tag{12}$$

Where $\mathrm{SINR}_{k,n}^{A}$ is effective SINR for k-user at n-th subcarrier using precoding $\mathbf{A}$. Then the spectral efficiency can be obtained from the following approach [10]:

$$\mathrm{SE} = \log_2\left(1 + \mathrm{SINR}_{k,n}^{A}\right) \tag{13}$$

The SE formula in (13) can be calculated numerically for different channel types and precoding schemes. The downlink SE for the k-th user in a cell really depends on the used of precoding. Therefore, choosing the most appropriate precoding technique is very important. By using precoding, each signal of precoded vector is sent from all antennas but with a difference amplitude and phase, so that the signal will be sent directly to users. To investigate the interfence gain at Rayeleigh and UR-LOS channel, suppose we have two users with channel response $\mathbf{h_1}$ and $\mathbf{h_2}$. The cummulative distribution function (CDF) of the interference gain is shown in (14)[10].

$$\mathrm{CDF} = \frac{1}{\beta} \frac{|(\boldsymbol{h_1})^H \boldsymbol{h_2}|^2}{\|\boldsymbol{h_1}\|^2} \tag{14}$$

For UR-LOS channel, (14) equals with $h(\varphi_1, \varphi_2)$ which is described in (15) [10].

$$h(\varphi_1, \varphi_2) = \frac{\sin^2 \pi d_H M((\sin(\varphi_1) - \sin(\varphi_2)))}{M \sin^2(\pi d_H (\sin(\varphi_1) - \sin(\varphi_2)))} \tag{15}$$

It can be seen that interference gain at UR-LOS channel in (15) is a function of M and user angle. Where only user with similar angle cause strong interference. While at Rayleigh condition, the interference gain in (16) is not depend on the value of M and user position, the desired user is affected by all user interference. Therefore, UR-LOS channel provides lower interference level than Rayleigh channel.

III. Numerical Results

A. Single Cell MU-Massive MIMO System

We simulated downlink scheme of single cell MU-Massive MIMO system which operates at a frequency of 6 GHz. We assumed that there is no intercell interference.

TABLE 1. OFDM Numerology

OFDM Parameters	Up to Frequency of 6 GHz
Number of subcarriers	512
Number of used subcarriers	300
Subcarrier spacing	15kHz
OFDM symbol duration	71.4μs
Useful symbol duration	66.77μs
Cyclic perfix duration	4.69 μs

BS uses ULA antennas with spacing between antenna elements is $\lambda/2$. The OFDM modulation scheme is used for data transmission, which parameters refer to OFDM numerology [1,9] as shown in Table 1. We consider a Rayleigh fading frequency-selective channel with L = 8 taps and has uniform power delay profile. Tapped delay lines can be used to represent sparse mutilpath channel for wireless communication system. The path between users and BS are affected by the same large-scale fading (β_k) but different small-scale fading (h_k). We assumed that all users large-scale fading coefficient equal to unity ($\beta_k = 1$). Then independent Rayleigh fading can be referred as identical independently distributed Rayleigh Fading (i.i.d Rayleigh fading).

B. Bit Error Rate (BER)

To evaluate BER of the system, we plot the BER as a function of SNR with the fixed number of BS antennas and users. BS is equipped with 100 antennas *(M)* and serves 20 users *(K)* simultaneously. In order to work properly, the number of BS antennas should be at least four times the number of users ($K \leq 4M$) [10]. All user posistions are random and uniformly distributed at interval $[{}^{-\pi}/_{2}, {}^{\pi}/_{2}]$.

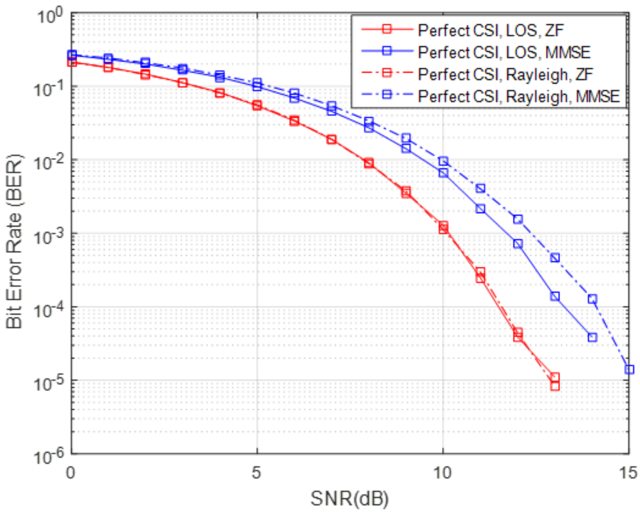

Fig. 2 BER MU-Massive MIMO at perfect CSI condition. In this example there are M = 100 antennas, K = 20 users.

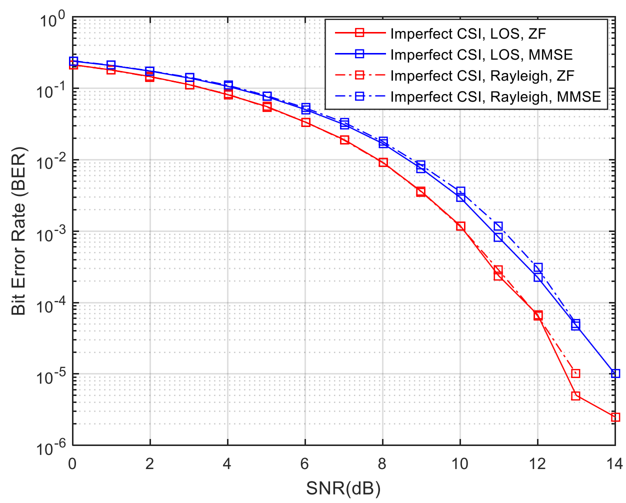

Fig. 3 BER MU-Massive MIMO at imperfect CSI condition. In this example there are M = 100 antennas, K = 20 users. τ_p = 20.

In perfect CSI condition, BER of system is shown in Fig. 2, while BER for imperfect CSI condition is shown in Fig. 3. The BER depends on the strenght of desired signal which represents as SNR. Increasing SNR means increasing the transmit power, which results smaller BER. From the graph of BER vs. SNR, it can be seen that ZF precoding has better performance than MMSE precoding both at Rayleigh or UR-LOS channels, marked with a smaller BER at the same SNR value. Furthermore BER in Rayleigh channel is slightly higher than in UR-LOS channel. This is because each user is affected by interferences from many other users, while on the UR-LOS channel only few users with similar angle cause strong interferences.

Then, we focus to investigate the system performance under imperfect CSI condition. BS estimates the channel response from pilot signal transmitted by users. The total number of pilots transmitted by each user must be greater or equal to the number of active users in a cell, therefore each user transmits 20 symbols of pilot sequences ($\tau_p = K$). This is the minimum number of pilots that can be sent by each user. The number of pilots limit how many user can be served simultaneously. After despreading pilot signals, BS can obtain a noisy version of the channel. Then, MSE of channel estimation can be calculated and shown in Fig. 4. Channel estimation error really depends on SNR at the BS, the higher the SNR, the channel estimation error will be smaller. The main different of Rayleigh and UR-LOS channel is the characteristic of their small-slace fading. When M is large, the effect of small-scale fading of the channel will be disappear, which known as channel hardening phenomenon [6]. This phenomenon makes MSE of channel estimation both at Rayleigh and UR-LOS channel almost have same value. Morover, At the same SNR value, BER in imperfect CSI condition is slightly higher than the BER in the perfect CSI condition due to the channel estimation error existance.

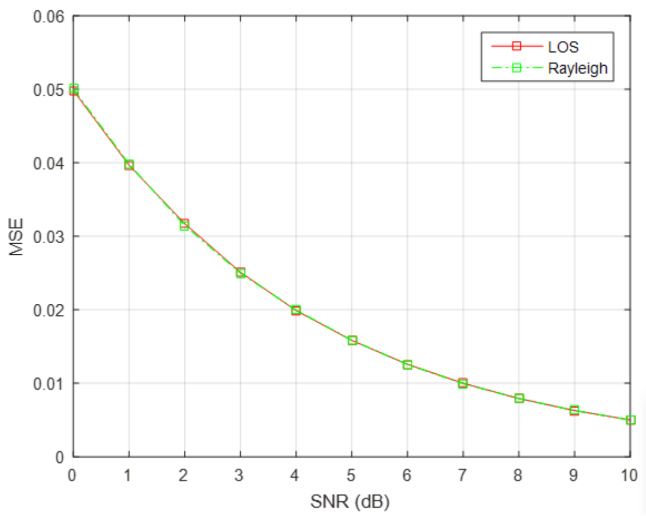

Fig. 4. Minimum Mean-Square Error (MSE) of estimated channel

C. Spectral Efficiency (SE)

Spectral efficiency is a deterministic number that can be measured in bits per time unit per bandwidh or commonly known as bit/s/Hz . Where the sum of SE is obtained from the sum of SE form all users in a cell. A high SE value is the main key objective in designing a wireless communication system. By increasing the number of antennas on the BS, the SE will be higher. In this simulation, SE is observed by increasing the number of BS antennas with a constant number of users. BS is equipped with a varying number of antennas, ranging from 50 to 300 and simultaneously serves 20 users. This system works on SNR of 10 dB, because BER on this SNR is small, which is $\pm 10^{-3}$ as shown in Fig. 1 and Fig. 2. The SE as a function of antenna variation in perfect CSI conditions is shown in Fig. 5. While the SE in the imperfect CSI condition is shown in Fig. 6. As seen in (12), the downlink SE of desired user is affected by precoding vector of all user that multipled with channel respons of serving BS, where multiplication between its own precoding and channel response will be a desired signal and the other multiplication of precoding and channel response will be interferences as shown in (12).

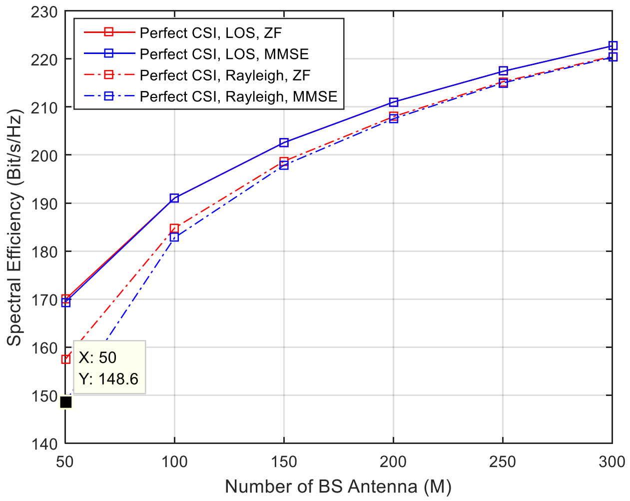

Fig. 5. Spectral Efficiency of MU-Massive MIMO at perfect CSI condition. In this example there are K = 20 users and the SNR = 10 dB

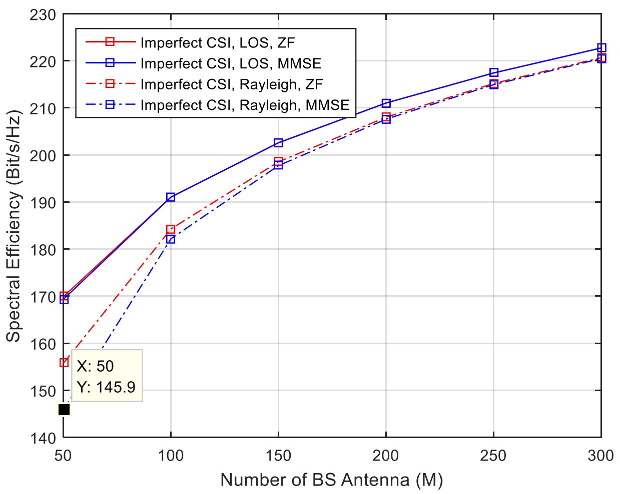

Fig. 6. Spectral Efficiency of MU-Massive MIMO at imperfect CSI condition. In this example there are K = 20 users and the SNR = 10 dB

Under the condition of Rayleigh channel, ZF precoding yields higher SE than MMSE precoding, however MMSE will work as well as ZF when the number of BS antennas is over 100. This condition will be different in LOS condition, where MMSE precoding works as well as ZF precoding almost in every number of antennas. Both in perfect CSI and imperfect CSI conditions, the total of SE will increase if the number of transmitter antennas increases.

The SE as a function of the number of users is shown in Fig. 7. We can see that sum SE will increase as the number of users increases on condition that the number of users is still smaller than the number of BS antennas $(K < M)$. At 100 fixed number of BS antennas, a significant increasing of SE occurs when the number of users is in range of 20 to 80. However, when the number of users is above 80, the SE is starting to flatten out a bit. This is because the maximum number of users that can be served by 100 BS antennas are 80 users. As in [10], the number of BS antennas should be much larger than the number of users, leading to an antenna-users ratio $(M/K \geq 1)$. This ratio makes linier precoding nearly optimal since multiuser interference is small. This condition will be different when the number of BS antennas is 30 and serves exceeds 30 users, then the SE started to decrease due to the high interference between users, and precoding is not able to overcome it.

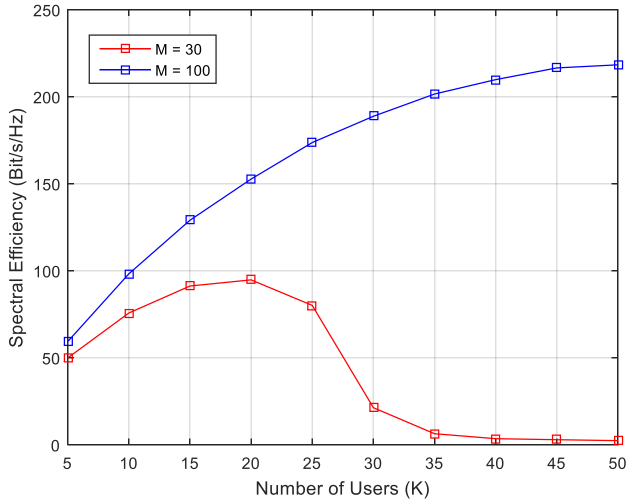

Fig. 7. Spectral Efficiency of MU-Massive with different number of users

IV. Conclusion

In this study, we investigated the performance of downlink scheme single cell MU-Massive MIMO system under perfect CSI and imperfect CSI condition. ZF and MMSE linear precoding techniques are implemented to reduce multiuser interference. We consider linier precoding because their low computational complexity and nearly optimal to use since the number of BS antennas is large. Both ZF and MSSE are suitable precoding technique for Massive MIMO system, where MMSE works better for a large number of antennas. At the same SNR value, BER of system using ZF precoding is smaller than using MMSE both at Rayleigh and UR-LOS channel. Meanwhile in Rayleigh channel, BER is higher and SE is smaller than in UR-LOS channel due to interference from the other users in a cell. In the imperfect CSI condition, BS estimated channel information from pilots sent by users, so that BS only knows the noisy version of channel. The spectral efficiency is slightly decreased under the imperfect CSI condition due to the error of channel estimation. Furthermore, MU-Massive MIMO system offers the possibility to increase SE significantly and serves multiple users at the same time-frequency resources.

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