Performance of Efficient Multi Cell Massive MIMO System

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***Abstract*—Massive multiple-input-multiple-output (MIMO) is the key technology to provide higher spectral efficiency (SE) and data throughput in the fifth-generation (5G) wireless technology. In this paper the performance of multi-user massive MIMO system is investigated under rician channel as the transmission range is quite short and dominant line of sight signal component. We have compared the performances like harvested energy, achievable rate in channel reciprocity error. Due to non reciprocal channel the performance of massive MIMO has been decreased. This reciprocity error in channel is due to RF mismatch in the transceiver at the base station (BS). Time division duplex (TDD) yields high performance as it is scalable and the pilot is independent of number of antenna at BS. Spectral efficiency has not seen any major improvements in the previous network generation. Various linear precoding techniques is used to maximize the SE of massive MIMO system without further increasing the bandwidth and antenna at base station. Pilot reuse technique is used to minimize the pilot contamination and co-channel interference. Bit error rate (BER) is negligible due to the large antenna array at BS. Also, Massive MIMO is energy efficient and noise & interference free wireless communication system.**

***Index Terms*—Massive MIMO, Spectral Efficiency, Channel Reciprocity Error, Time Division Duplex, Linear Precoding, Pilot Contamination.**

I. Introduction

Massive MIMO is one of the key enabling technology to establish the 5G wireless communication technology [1]. Simultaneous wireless information and power transfer between the BS and user terminal (UT) increases the efficiency of the system [2]. In downlink, BS charges the user by transferring energy to UT i.e, multi-user beam forming. The harvested energy is exploited by the users to communicate with the BS on the uplink. Uplink is the wireless information transfer from the UT to BS i.e, multi-user detection. The downlink transmission is estimated by the uplink data transmission. But, due to the RF mismatch in the hardware chain at the BS transceivers channel may not be reciprocal between the uplink and downlink [3]- [4]. The downlink pilot should be mutually orthogonal between the antennas, also the number of response of the channel estimated should be proportional to the number of BS antenna. So, the TDD mode is more optimistic in this situation which rely on the reciprocity between the uplink and downlink. TDD is considered as more spectrum efficient and reliable for growing data traffic. Harvested energy and achievable rate increases with the increment in BS antenna. But, in this finite world we can't use the infinite antenna at BS [5]. There is some limit which is decided by energy efficiency of the system [6]. If we increase the antenna at BS, circuitry power consumption, complexity and deploying cost of the system will increase, achievable rate gets constant after the energy efficient regime of massive MIMO, and the energy efficiency will decrease due to increase in the circuitry power consumption. So, we have tried to quantify the massive MIMO. In the previous network technology SE has not seen the major improvement in it. As the global demand for wireless data traffic is increasing also new technology like internet of things (IOTs) are evolving and around 20 to 50 billion devices will be internetworked by 2020. Also wireless traffic is doubled every two year in last few decades, also the rate is increasing now a days. So, there is a improvement needed in area and data throughput [7] . The 5th generation network technology will also provide better addressing technique to billions of inter networked devices. Massive MIMO scale the SE by several tens and hundreds using different linear precoding process [8]. zero forcing (ZF) precoding witness the higher performance in noiseless system while as maximum ratio (MR) estimate efficiently with respect to channel state information (CSI). But there is a major drawback of ZF in previous network technologies, as it amplify the noise. But, the massive MIMO system is noise and error free so ZF will enhance the performance, as it is ideal for the noiseless system. Available resource bandwidth divided into different disjoint group of different frequency range i.e, pilot reuse factor or sub bands to reduce the pilot contamination [9]- [10]. Interference is more at the boundary of the cell. As per the user density different pilot reuse factor can be used to maximize SE [11]. In low user density, pilot reuse factor can be increased to minimize the interference while as it can be reduced in the high user density so that the full resource is available to the users.

In this paper, we have compared the simultaneous wireless information and power transfer performances like harvested energy, achievable rate of massive MIMO in channel reciprocity and channel estimation error i.e, channel reciprocity error. After that we have maximized the area or data throughput by increasing the spectral efficiency of massive MIMO without increasing the bandwidth and cell density. Performance of massive MIMO system is analyzed in various linear precoding scheme like ZF and MR and it is shown that TDD mode is more suitable for massive MIMO system. We have also tried to quantify the meaning of massive by deriving the energy efficient regime of massive MIMO. We used the various pilot reuse factor to minimize the pilot contamination in order to optimize the spectral efficiency for different user density per cell. BER performance is also analyzed in this paper.

II. System Model

We considered a multi user massive MIMO system having M number of BS antenna and K users at user terminal ($M >> K$). The total area of coverage is divided into number of cells. Hexagonal cells which is very near to a circle is used to distribute the users. In a coherrent interval time T, τT ($\tau < 1$) of time is used for training of channel and remaining $(1 - \tau T)$ is used for information and power transmission. In FDD downlink and uplink is simultaneously happening with having a extra guard bandwidth separated in between which results in loss of bandwidth. TDD mode is acceptable because of the reciprocity of the system. In TDD the whole bandwidth is used for downlink and uplink transmission. Hence, TDD is the preferable mode since it not only requires the shorter pilot than FDD but also highly scalable as the pilot length is independent of M.

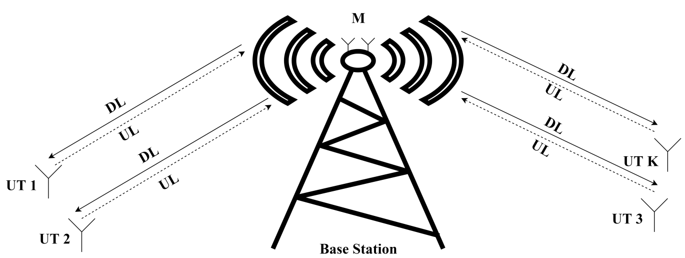

Fig. 1. A generic Massive MIMO system having M antenna at BS and K UT.

Channel Matrix: Since, the transmission range is quite short in massive MIMO system, there is dominant line of sight propagation present, the small scale fading envelope distribution is rician. The pdf of rician fading can be expressed as:

$$F_R(r) = \begin{cases} \frac{r}{\sigma^2} e^{-(\frac{r^2+A^2}{2\sigma^2})I_o(\frac{Ar}{\sigma^2})} & 0 \leq r < \infty, A \geq 0 \\ 0 & otherwise \end{cases} \tag{1}$$

Where A is the peak amplitude of the dominant signal. $I_o()$ is the modified bessel function of the first kind and zeroth order. The rician distribution can also be described in terms of parameter 'K' which is called as rician factor which is the ratio of deterministic signal power and variance of the multipath envelope.

$$K_{dB} = 10log(\frac{A^2}{2\sigma^2}) \tag{2}$$

The channel vector between BS and k-th user is given as:

$$\mathbf{h}_k = \sqrt{\frac{\beta K}{K+1}}\mathbf{A} + \sqrt{\frac{\beta}{K+1}}\mathbf{Z} \tag{3}$$

Here, $\beta = Cd^{-\alpha}$ is the large scale fading depend on the distance d between BS and user. $\mathbf{A}$ denotes the deterministic signal component, $\mathbf{Z} \sim \mathcal{N}(0_M, I_M)$ denotes the random component of the k-th user.

III. Channel Reciprocity Error Modelling

Due to the fact that the imperfection of the channel reciprocity affect the system performance which occurs due to the RF mismatch in the transceiver at the BS, we focus on the reciprocity error at the BS. The effective response of the transmit antenna at the BS is given by H_t as follows:

$$\mathbf{H}_t = diag(h_{t,1}, h_{t,2}, h_{t,3}, \ldots, h_{t,m}, \ldots, h_{t,M}) \tag{4}$$

where, $h_{t,m}$ represents the effective response of the m_{th} transmit antenna at the BS. (The subscript t is for the transmitter end of the transceiver at the BS). Mathematically,

$$h_{t,m} = A_{t,m}e^{j\phi_{t,m}} \tag{5}$$

$A_{t,m}$ represents the amplitude response and $\phi_{t,m}$ represents the phase response of the m_{th} transmitt antenna at the BS. $A_{t,m}$ and $\phi_{t,m}$ are truncated Gaussian distribution since it is more realistic in comparision to the uniformly distributed model, as the negligible power component is ignored. The amplitude and phase error is given by truncated gaussian as:

$$A_{t,m} \sim \mathcal{NT}(\mu, 0, \sigma^2) \ , A_{t,m} \in [a, b]$$

$$\phi_{t,m} \sim \mathcal{NT}(\mu, 0, \sigma^2) \ , \phi_{t,m} \in [\theta_1, \theta_2]$$

The effective response of the receive antenna of the transceiver at the BS is given by H_r as follows:

$$\mathbf{H}_r = diag(h_{r,1}, h_{r,2}, h_{r,3}, \ldots, h_{r,m}, \ldots, h_{r,M}) \tag{6}$$

where, $h_{r,m}$ represents the response of the m_{th} receive antenna of the transceiver at the BS. (The subscript r is for the receiver end of the transceiver at the BS). Mathematically,

$$h_{r,m} = A_{r,m}e^{j\phi_{i,m}} \tag{7}$$

$A_{r,m}$ represents the amplitude response and $\phi_{r,m}$ represents the phase response of the m_{th} receive antenna at the BS. We have taken $A_{r,m}$ and $\phi_{r,m}$ as truncated Gaussian distribution and ignored the negligible power component. The amplitude and phase error of receiver of the transceiver at the BS is given by truncated gaussian distribution as:

$$A_{r,m} \sim \mathcal{NT}(\mu, 0, \sigma^2) \ , A_{r,m} \in [a, b]$$

$$\phi_{r,m} \sim \mathcal{NT}(\mu, 0, \sigma^2) \ , \phi_{r,m} \in [\theta_1, \theta_2]$$

Thus, the reciprocity error matrix is given as:

$$\mathbf{E}_r = \mathbf{H}_t\mathbf{H}_r^{-1} = diag(\frac{h_{t,1}}{h_{r,1}} \ldots \frac{h_{t,m}}{h_{r,m}} \ldots \frac{h_{t,M}}{h_{r,M}}) \tag{8}$$

The channel matrix after considering the reciprocity error i.e, effective channel response is given as:

$$\mathbf{H}_{ij} = [diag(\mathbf{h}_k)]\mathbf{E}_r = [\mathbf{H}_k]\mathbf{E}_r \tag{9}$$

When, $\mathbf{E}_r = 1$ i.e, ($\mathbf{H}_{it} = \mathbf{H}_{ir}$) then the channel is completely reciprocal i.e, downlink is estimated via uplink transmission.

IV. Massive MIMO Performance

A. Uplink Channel Estimation

A mutually orthogonal pilot sequence vector each of length L_p, is assigned randomly to all the users for uplink pilot transmission to the BS. The pilot sequence matrix is of the size $L_p \times K$. The estimated channel oh $\mathbf{h}_k$ after the minimum mean square error (MMSE) estimation is $\hat{\mathbf{h}}_k$ that minimizes the mean square error (MSE) i.e, $\mathbf{E}|| \ \mathbf{h}_k - \hat{\mathbf{h}}_k \ ||^2$ is minimum. The uplink estimated channel vector is represented as:

$$\hat{\mathbf{h}}_k = \sqrt{zK}\mathbf{A} + \left(\frac{z\sqrt{p_L L_p}}{zp_L L_p + \sigma^2}\right)(\sqrt{zp_L L_p}\mathbf{Z} + \mathbf{n_k}\phi_k) \quad (10)$$

where, $z = \frac{\beta}{K+1}$, $\mathbf{n}_k \sim \mathcal{CN}(\mu, \sigma^2)$ is a independent and identical complex gaussain noise, $\phi_k \sim \mathcal{CN}(\mu, \sigma^2)$ represent the pilot signal transmitted in uplink by the k_{th} user and p_L represent the power of the transmitted pilot signal by k_{th} user.

B. Dowlink Transmission:

In downlink transmission, information signal and power is transmitted to the user k. The information signal transmitted to k_{th} user is denoted as x_k. The signal $\mathbf{y}_k$ received at k_{th} user is denoted as:

$$\mathbf{y}_k = \underbrace{\sqrt{p}_k \mathbf{h}_k^H \mathbf{w}_{lk} x_k}_{\text{desired signal}} + \underbrace{\sum_{j \neq k}^{K} \sqrt{p}_j \mathbf{h}_k^H \mathbf{w}_{lk} x_j}_{\text{interference signal}} + \underbrace{\mathbf{n}_k}_{\text{noise signal}} \quad (11)$$

where p_k represent the transmitted power and $\mathbf{w}_{lk}$represents the linear precoding vector of the k_{th} user. While using ZF precoding matrix $\mathbf{w}_{lkZF} = \mathbf{H}^\dagger = (\mathbf{H^H H})^{-1}\mathbf{H^H}$ for the received signal $(\mathbf{w}_{lkZF})\mathbf{y} = x + \mathbf{w}_{lkZF}\mathbf{n}_k$. Thus, the ZF precoding amplify noise and it is ideal for the noiseless system. Precoding vector for ZF is given as:

$$\mathbf{w}_{lkZF} = \frac{\hat{\mathbf{H}}^\dagger}{\sqrt{\mathbf{E} || \ \hat{\mathbf{H}}^\dagger \ ||^2}} \quad (12)$$

Precoding vector for MR is given as:

$$\mathbf{w}_{lkMR} = \frac{\hat{\mathbf{h}_k}}{\sqrt{\mathbf{E} || \ \hat{\mathbf{h}_k} \ ||^2}} \quad (13)$$

n_k is complex additive white Gaussian noise $\mathbf{n}_k \sim \mathcal{N}(0,1)$. ρ_k fraction of received power is used for the decoding information while as remaining fraction $(1-\rho_k)$ is used for harvesting energy. The energy harvested by the k_{th} user is given as:

$$E_k = \eta_k \mathbf{E}[| \ h_k^H \sum_{t=1}^{K} p_t w_{lk} \ |^2] \quad (14)$$

Here, η_k is the conversion efficiency at the UT.

C. Spectral Efficiency

Achievable rate depends on the signal-to-noise-plus-interference ratio (SINR). Spectrum efficiency is the efficient use of bandwidth so that the maximum amount of data can be transmitted with minimized errors. Spectral efficiency which is measured in bits/s/Hz per unit area or bits/s/Hz/cell is upper bounded by the shanon capacity or achievable rate i.e, $(1-\tau) \times log_2(1+SINR)$. ρ_k is the fraction of power used for the decoding information. The Achievable Rate (bits/s/Hz) of the k_{th} user is given as:

$$R = (1-\tau) log_2 \left(1 + \frac{\rho_k p_k \mathbf{E}(| \ \mathbf{h}_k^H \mathbf{w}_{lk} x_k \ |^2)}{\mathbf{E} \ | \ \sum_{j\neq k}^{K} \sqrt{p}_j \mathbf{h}_k^H \mathbf{w}_{lk} x_j) \ |^2 + \sigma_n^2}\right) \quad (15)$$

D. Area Throughput

To keep up with the rapid increasing traffic growth, a key goal of the 5G technologies is to improve the area throughput by orders of magnitude hundred times, higher throughput are regularly mentioned as 5G design goals.

$$Throughput = BW * CD * SE \quad (16)$$

Here, bandwidth (Hz) is denoted as BW and cell density (cells/km^2) is denoted as CD and spectral efficiency (bits/sec/Hz per unit area) or (bits/sec/Hz per cell) is denoted as SE. The improvement in area throughput in previous network generation technology has increased by the cell densification and the allocation of more bandwidth. The spectral efficiency has not seen any major improvement in previous network generations. Hence, it might be a factor that can be greatly improved in the future and possibly become the primary way to achieve high area or data throughput in 5G networks.

E. Energy Efficiency

Energy efficiency is simply achievable rate per unit power consumption at the base station. Its unit is bits/sec/joule. The power consumed is in the form of circuitry power consumption and transmitted power. The circuit power consumption includes, the computational power, $P_c = \frac{2MK^2B}{S\eta_{BS}}$. η_{BS} is the computational efficiency, it is measured is flops/watt and $\frac{B}{S}$ is coherence block per second. KRP_d is the power consumed in decoding the received data, R is an user average achievable rate and P_d is the power consumption by the decoder. P_l is the power consumed in the linear precoding process at BS for ZF processing power consumed is $\left(\frac{B(\frac{K^3}{3}+3MK^2+MK)}{S\eta_{BS}}\right)$. Energy efficiency is given as:

$$EE = \frac{(1-\tau)log_2\left(1 + \frac{\rho_k p_k \mathbf{E}(|\mathbf{h}_k^H \mathbf{w}_{lk} x_k|^2)}{\mathbf{E}|\sum_{t\neq k}^{K} \sqrt{p}_j \mathbf{h}_k^H \mathbf{w}_{lk} x_j)|^2 + \sigma_n^2}\right)}{KRP_d + \frac{2MK^2B}{S\eta_{BS}} + \left(\frac{B(\frac{K^3}{3}+3MK^2+MK)}{S\eta_{BS}}\right) + P_f} \quad (17)$$

Here, P_f is the fixed power consumption in deploying antenna at BS.

F. Frequency Reuse Factor

Each cell has been allocated a frequency band. Each channel is equidistant from its co-channel and hence the co-channel interference is optimally distributed. F is called as the frequency reuse factor or pilot reuse factor that is given as:

$$F = i^2 + ij + j^2 \quad (18)$$

Here, i is the number of cells in horizontal direction and j is the number of cells i.e, 60° to the horizontal direction. For the value of i=(0,1,2...) and j= (0,1,2...), F can take the value (1,3,4,7...). We note that with a pilot reuse factor of f = 7, one can divide the cells into seven different disjoint group of different frequency range. As Interference is more likely to occur at the boundary of the cell than the center of the cell. So, we can divide each cell into two subcells: cell edge and cell center. The latter is known as fractional pilot reuse. Pilot reuse factor is increased to minimize the pilot contamination or co-channel interference, but it divides the available resource bandwidth.

G. Bit Error Rate Performance

Massive MIMO is the asymptotically noise and interference free communication. BER is almost negligible as the number of antenna is too large at the base station and the mobile station. The BER in multi antenna system is given as:

$$BER \approx \binom{2M-1}{M}\left(\frac{1}{SNR}\right)^{M} \tag{19}$$

For low SNR, BER is almost negligible. Thus, massive MIMO is a errorless and noise free communication system.

V. SIMULATION RESULTS

We have evaluated the performance of massive MIMO system by our simulated results in MATLAB. In our system we varied the number of antenna at BS and user upto few hundreds in order to quantify the efficient number of BS antennas and multi users at UT. The SINR is taken as 20dB, coherence time $\tau_c = 600ms$. The pilot length L_p equals to K. Power splitter coefficient (ρ_k) is taken in between 0.4 to 0.6. The average harvested energy result also indicate that the amount of the harvested energy increases with the number of antennas at BS as shown in Fig. 2. The harvested energy is simulated for different values of amplitude error in channel estimation with having power 1dB, 4dB, 6dB and 8dB and it is seen that the energy exploited by user is decreasing with the increase in the power of the amplitude of the channel reciprocity error modelling. It is seen in Fig. 3, that the achievable rate is increasing with increase in number of antennas at BS and the curve getting constant after some instant. Also the rate performance is affected due to reciprocity error and it is decreased. In Fig. 4, spectral efficiency for different number of base station antenna is plotted by using MR precoding algorithm. MR precoding estimates better with respect to perfect CSI. Simulation result shows that TDD mode is having better performance than FDD mode. In TDD, pilot sequence is independent of the number of antenna at BS and all the available resource is used in communication process divided in time slots. In FDD, frequency is divided in between different users at the same time, so by increasing more number of BS antenna will not improve the spectral efficiency of the system, as there will be simultaneous communication between transmitter and receiver. So, after the minimum of pilot length sequence (L_p) and BS antenna (M), the spectral efficiency gets constant in FDD.

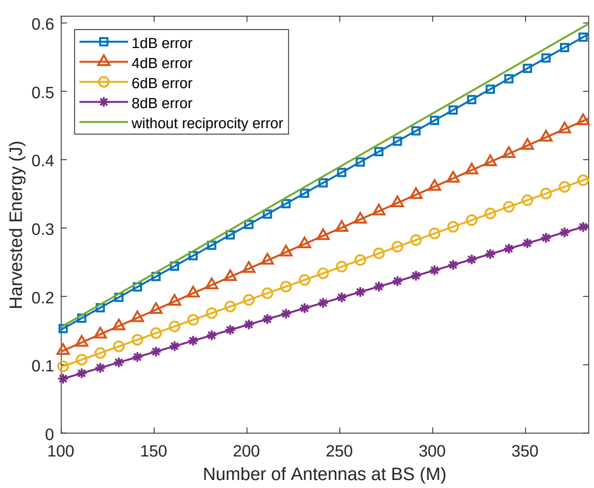

Fig. 2. Average harvested energy versus number of antennas at BS for different values of reciprocity error amplitude.

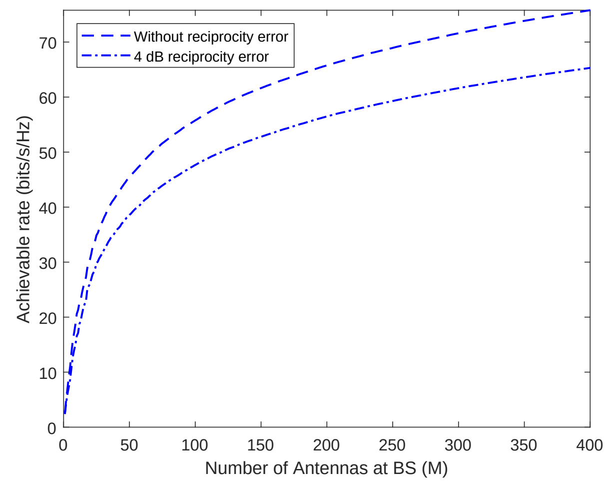

Fig. 3. Average achievable rate versus number of antennas at BS.

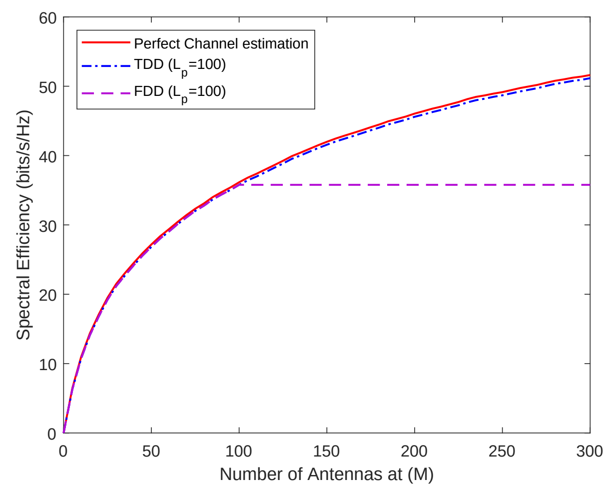

Fig. 4. Average downlink spectral efficiency versus number of BS antennas is plotted with maximum ratio precoding $(L_p = 100)$.

In Fig. 5, spectral efficiency for different number of base station antenna is plotted for ZF precoding algorithm. It is seen that spectral efficiency performance has increased in ZF than MR precoding because Massive MIMO is noiseless communication system. Thus, the noise amplification in zero-forcing is negligible. But, ZF precoding is not the better estimate with respect to perfect channel state information. Hence, ZF precoding is preferred over MR precoding in noiseless communication system for the enhanced performance. By inceasing number of antenna at BS, massive MIMO performance can be enhanced but there is some limit which is bounded by energy efficiency. By increasing the number of antenna at BS, the deploying cost and circuit power consumption will increase which will give less energy efficient system as the achievable rate getting constant after some instant. Here we tried to quantify the

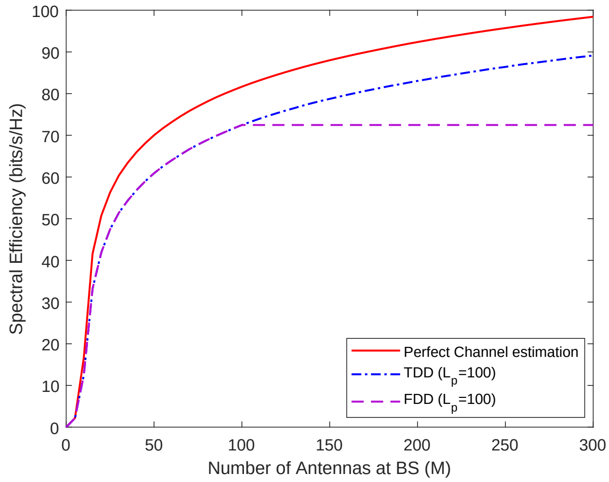

Fig. 5. Average downlink spectral efficiency versus number of BS antennas is plotted with zero forcing precoding ($L_p = 100$).

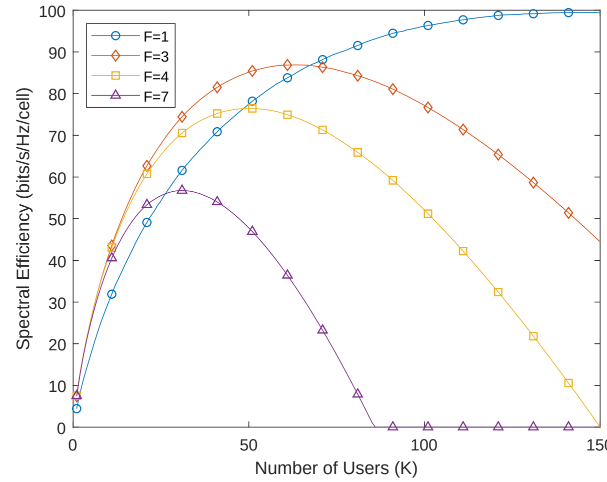

Fig. 7. Average spectral efficiency versus the number of users, with maximum ratio precoding and different pilot reuse factors at SNR=10dB.

meaning of massive. In Fig. 6, we concluded that massive MIMO regime is around few hundreds (300-400) of antenna array at BS. After that by increasing more number of antennas at BS will lead to the less energy efficient and complex system. In Fig. 7, for MR precoding, full resource is availabe to the users when pilot reuse factor is 1 and it is more efficient for high user density, as in plotted graph, more than 70 users per cell is efficient. Increasing pilot reuse divide the available resource in between users and it is preferred for the low user density. Pilot reuse factor is increased in order to reduce the contamination or interference between users. F=3 is preferred for 20 to 70 users per cell, F= 4 is preferred for around 10 to 20 users per cell and F=7 is preferred for less than 10 users per cell. In Fig. 8, for ZF precoding, F=1 is preferred when there is more than 90 users per cell, F=3 is preferred for 20 to 90 users per cell, F=4 is preferred for 10 to 20 users per cell and F=7 is preferred for less than 10 users per cell. Results show that ZF gives better SE performance than MR precoding and MR precoding gives the better estimation with respect to perfect CSI.

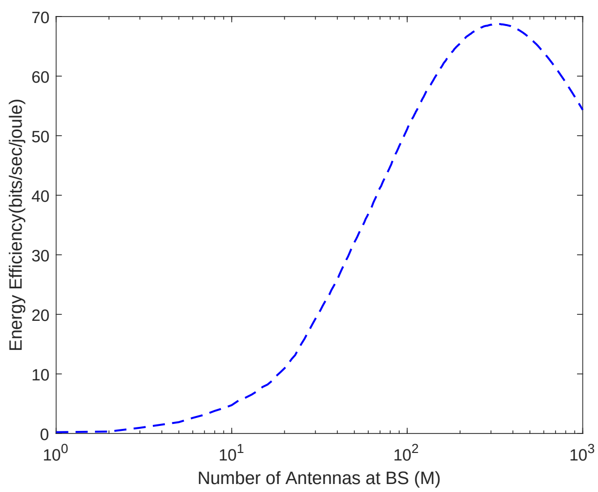

Fig. 6. Energy efficiency curve.

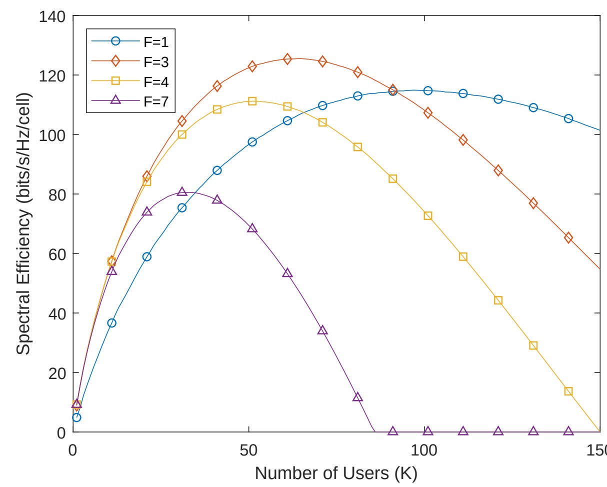

Fig. 8. Average spectral efficiency versus the number of users, with zero forcing processing and different pilot reuse factors at SNR=10dB.

In Fig. 9, The number of users is optimized for the different number of BS antenna to yield the highest spectral efficiency, and the corresponding number of users is also shown. In 4G network communication system, spectral efficiency is in the range of 2-4 bit/s/Hz/cell. The Massive MIMO network as considered in simulated result in Fig.9 achieves 53 bit/s/Hz/cell using M=100 antennas, which is a 20 times improvement over 4G network, With M=400 antennas the Massive MIMO system achieves around 112 bit/s/Hz/cell, which is an incredible 40 times improvement over previous generation network. Thus, spectral efficiency and number of user is maximized in 5G communication. As the plotted result in Fig. 10 and Table I, It is shown that by increasing number of antenna at BS leads to decrement in BER drastically. Hence for large antenna system model as in massive MIMO, BER is negligible and it is in the order of 10^{-70} for 5dB SNR at M=340 as shown in Fig. 11. Hence, we can say that the massive MIMO is error free communication system due to large number of antenna at base station and more number of user served simultaneously.

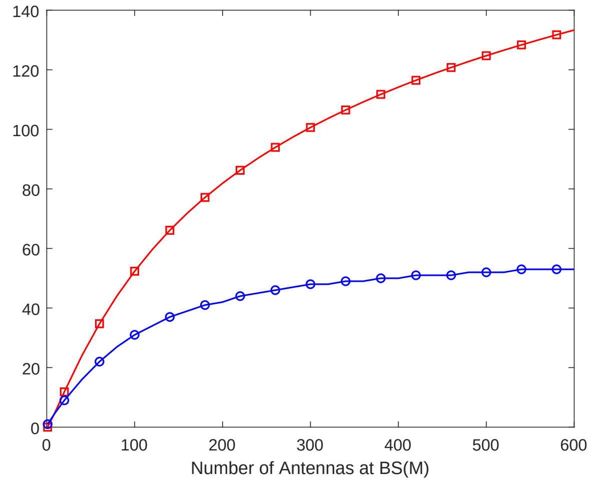

Fig. 9. Average spectral efficiency versus the number of BS antennas, with ZF processing at pilot reuse factor f = 3, and an SNR of 10 dB, and the corresponding number of users to achieve the highest spectral efficiency.

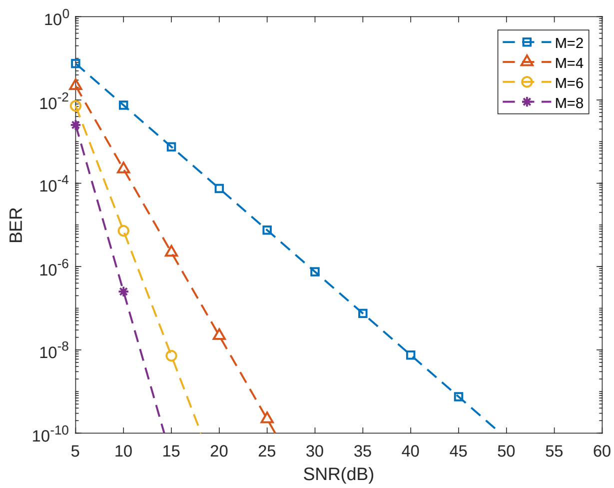

Fig. 10. BER versus SNR(dB) for different smaller values of BS antenna M.

VI. Conclusion

We have evaluated the performance of massive MIMO in this paper, we have analyzed the average harvested energy and achievable rate of massive MIMO under rician fading channel. Also, due to channel reciprocity error performance has decreased. We have quantified the term massive through energy efficiency curve. We used various linear precoding scheme to estimate the channel state information and maximize the spectral efficiency. We have used the technique of frequency reuse to minimize pilot contamination. Frequency reuse factor is increased when user density is less and vice versa for user's resource optimization. Also, we have seen that massive MIMO gives around 40 times more spectral efficiency than the previous 4G network technology. Simulated result shows that massive MIMO is also a error and interference free communication system, for small value of SNR, bit error rate is negligible. Hence, we have analyzed the performance of energy efficient multi cell massive MIMO system.

TABLE I
SNR and BER for different value of M.

M(No. of antenna)	SNR(dB)	BER(approx.)
2	49	10^{-10}
4	26	10^{-10}
6	18	10^{-10}
8	14	10^{-10}
340	5	10^{-70}

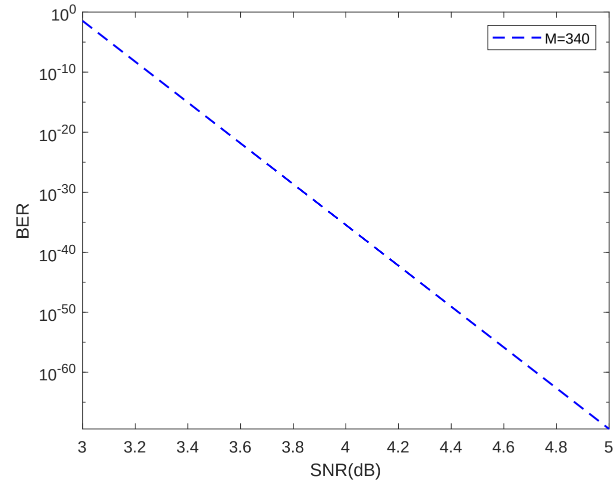

Fig. 11. BER versus SNR(dB) at M=340.

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