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Optimization of Spectral Efficiency in Massive-MIMO TDD Systems with Linear Precoding

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Abstract

Massive Multiple input multiple output (MIMO) antenna system, with hundreds or thousands of antennas at the base station and number of simultaneous active users in each cell, is a promising technology for the future to meet the ever growing needs of wireless data traffic. Since wireless spectrum is a limited resource maximizing the spectral efficiency (SE) of the available spectrum is the best option to meet the growing demand of wireless data traffic. In this paper we analyse the different ways to optimize the spectral efficiency (SE) of a massive MIMO in Time Division Duplex (TDD) architecture. The system performance under various practical constraints and conditions such as limited coherence block length, number of base station (BS) antennas, and number of active users are evaluated through simulation. The SE performance is also compared under different linear precoding techniques zero forcing (ZF) and maximum ratio combing (MRC). Simulation results demonstrated that a massive MIMO with hundreds of BS antennas can easily achieve very high improvements in the spectral efficiency.

Keywords: Massive MIMO, Spectral efficiency, Coherence block length, Channel state Information, Time division duplex, Linear precoding.

INTRODUCTION

Massive multiple-input multiple-output also known as large scale antenna systems proposed in [1], a new research area in wireless communications, is identified as the best way to maximise the spectral efficiency of wireless communication system. Massive MIMO in which the base stations are equipped with very large number of coherently operating antennas provides both diversity gain and multiplexing gain. Massive MIMO increases the data rate to a large extent because of the large number of antennas. Each antenna can send out independent data streams and more number of terminals can be served simultaneously giving full band width to each terminal. It can increase the capacity to 10 times or more because of the multiplexing used.

Massive MIMO can be built with inexpensive, low power components because the expensive ultra linear 50W amplifiers used with conventional systems are replaced by hundreds of low power amplifiers of mW range[2], [3]. It reduces the constraints on accuracy, linearity and RF gain requirements of the amplifiers used. It provides highly enhanced energy efficiency as the BS can focus the emitted energy to the spatial directions where the users are exactly located [4], [5]. Since it uses the pointed beam to the terminal it reduces the interference to other channels. Massive MIMO enables a significant reduction of latency in the air interface because it relies on the law of large numbers and beam-forming in order to avoid fading dips. Massive MIMO simplifies the multiple access layer because the channel hardens so that frequency domain scheduling no longer pays off and also each terminal can be given with the full bandwidth, which renders most of the physical layer control signalling redundant. Massive MIMO increases the robustness to intentional jamming because it offers many excess degrees of freedom that can be used to cancel signals from intentional jammers. These large surplus degrees of freedom can be effectively used for hardware friendly signal shaping. All these remarkable gains can be achieved with very low complexity linear signal processing methods [6]–[8].

All the adverse effects of uncorrelated noise and fast fading disappear and the only remaining impediment in massive MIMO is the inter-cell interference due to pilot contamination. Therefore, massive MIMO has been considered as one of the most sought-after and innovative technologies for the fifth-generation wireless communication systems [2], [9].

There is always a rapidly growing demand for wireless data. The only way to cater the growing demand is by providing higher throughput per unit area (bits/m^2). This can be achieved by increasing the cell density (more number of cells for a specific area) and by technical improvements in the physical layer to provide more spectral efficiency. The second possibility is examined in this paper where different methods to maximise the spectral efficiency of a massive MIMO system are studied. The effect of the number of BS antennas, number of active users per cell and coherent block length on the spectral efficiency is thoroughly examined through simulation. Zero forcing precoding technique is considered for our analysis and the results are also compared with maximum ratio combining method.

The remaining part of the paper is organised as follows. Section II gives a brief literature review to justify the relevance of the proposed work. Section III describes the system model under consideration and gives its characteristics. Section IV gives the details of simulation outcomes and the effect of various system parameters on SE and section V summarises the work and explains the insights attained through it.

Massive MIMO

Massive MIMO communication technique, where hundreds or a few thousands of antennas are deployed at the BS of a wireless cellular network, promises significant performance gains in terms of spectral efficiency, energy efficiency, security and reliability compared with conventional MIMO [10] and is now becoming a cornerstone of future 5Gsystems [11]. In [12]–[14] different schemes used for the implementation of Massive MIMO in wireless networks are explained. For a Massive MIMO system guide lines for allocating resources, intelligent allocation of orthogonal pilot sequence to appropriate cells for effective interference reduction and spatial correlation techniques etc. are analysed in [15], [16].

In centralized MIMO where receive and transmit antennas are co-located both at the receive and transmit side and in Distributed MIMO base station antennas are placed at different physical locations and connected through wide band fibre optic links. C-MIMO is practically easy to install and for theoretical analysis. D-MIMO suffers from various levels of path losses and in turn its analysis becomes very complex. However D-MIMO has advantages such as high spectral efficiency, better coverage area, improved multiplexing gain and better network planning [17], [18]. In [19] a generic channel model, meeting the requirements of both massive C-MIMO and D-MIMO with all important physical parameters and environmental parameters, is developed and tested using simulations.

The impact of massive analogue to digital converters on the SE of flat fading channels in massive MIMO systems are thoroughly studied in [20], [21]. It assumes Rayleigh fading channel and one bit resolution for the ADC which is often not true in line-of-sight wireless communications. In[22] SE of massive MIMO systems in Rician fading channels with low resolution ADCs are investigated under perfect and imperfect Channel State Information (CSI). It shows how the Rician K factor and base station antenna numbers and the ADC resolution affect the uplink SE.

For frequency division duplexing (FDD) systems the overhead incurred by pilot signals in the training process for collecting the channel state information increases linearly with the number of transmitting base station antennas. This puts an upper limit on the performance improvement which can be expected by the increase of base station antennas processed together in FDD systems as shown in [23] and [24]. In the case of Time division duplexing systems (TDD) channel state information at the transmitters is acquired from the uplink pilot signals using channel reciprocity technique [25]. In this method the training overhead increases linearly with the number of active users in a cell, who are served at the same time in a particular time-frequency slot. Unlike FDD systems here in TDD the training overhead is independent of the number of base station antennas used and hence the performance of the massive MIMO system can be considerably improved by scaling the number of base station antennas. In [1] Marzetta proved that the simple Linear Single-User Beam-Forming (LSUBF) and random user scheduling, can give a significant increase in the spectral efficiency of TDD cellular systems without any combined processing in the base station antennas with a condition that for each active user large number of transmitting antennas are used at each base station. The concept of dynamic clustering of cooperating base stations and multi user MIMO in a mixed mode have been discussed in vast published literatures [26]–[30]. In [31] a wireless communication network with MIMO TDD architecture, which requires fewer number of antennas per active user, has been studied and shown that it can reach spectral efficiencies that are comparable with the Massive MIMO scheme.

Macro cells with massive MIMO base stations (BSs) on highly concentrated small cells are studied in [32]. They have shown that the utilization of excessive number of antennas at the base station for interference management greatly improves the throughput and gives extended coverage. Different precoding schemes used for massive MIMO wireless systems are analysed in [33] and it is evaluated by using simulation models. Massive MIMO characteristics under large scale fading with perfect and imperfect CSI are analysed in [34] and an expression for SE is derived as a function of the number of transmitting antennas, number of users and the transmit power. These expressions are validated through simulations for different large scale fading parameters.

In [35] mathematical expressions for SE are derived which are valid for the uplink as well as downlink transmissions and are evaluated using matlab simulation models considering both maximum ratio combining and zero forcing methods for channel estimation.

Energy efficiency is another important measure of performance and is studied under imperfect and perfect channel state conditions in [2], [36]. In [37] four different power management schemes are designed under various channel estimation. techniques and its performance is evaluated using simulation models. The SE is analytically compared between two channel estimation methods and also evaluated the performance of full duplex and half duplex modes of operation. It is demonstrated that the energy efficiency is steady as the number of relay antennas increases to infinity. In [11] an energy efficient resource allocation scheme for massive MIMO FDD systems is investigated and numerical results are obtained. In [38] MMIMO and small cell networks are compared and showed that the small cell systems perform better in terms of the energy efficiency and massive MIMO outperforms in terms of rate performance and spectral efficiency in all operating conditions. In [39] multi-cell massive MIMO downlink system using non-coherent joint transmission is optimized to have minimum transmit power consumption keeping all the QoS fulfilled.

The energy efficiency and spectral efficiency of multi-layer full duplex amplify and forward relay systems are studied in[40], [41] and it shows that massive MIMO antennas can normalise the small scale fading by using simple signal processing methods and thereby minimise the transmitted power without affecting the performance of the system.

Spectral efficiency is an important performance measure in wireless cellular networks. The area spectral efficiency and area energy efficiency of a multiuser massive MIMO wireless cellular system is theoretically examined in [42] and obtained the system parameters for maximum area spectral efficiency. They have considered the pilot contamination effect and derived a general and closed form approximation for area spectral efficiency in a cellular system with massive MIMO. Pilot contamination is the main problem associated with massive MIMO multi-cell environment [43] and a number of efficient schemes for decontamination of the pilot are explained in [44], [45]. The impact of pilot contamination on the spectral efficiency has been considered in detail in[16], and [46] gives a vigorous study on this under various channel conditions. However there still exist some adverse factors that affect the performance of the TDD systems in practice, such as calibration error in uplink and downlink radio frequency chains and problems due to hardware impairments [47], [48].

In this work the effect of different linear precoding schemes, the number of BS antennas, number of active users per cell and coherent block length on the spectral efficiency is systematically studied through simulations.

System Model

Cellular network architecture was evolved to meet the ever growing needs of the wireless data traffic. The simple formula to calculate the network throughput in cellular networks is given by Throughput (bits/s) = Cell density (cell/area) × Available spectrum (Hz) × Spectral efficiency (bits/s/Hz/cell). This equation holds three components and hence three different options are available to improve the throughput of wireless communication network. First one is to increase the cell density which is the most traditional way to improve throughput in which dividing the cell radius by a factor of n will give us n^2 number of more cells. This method is very expensive in terms of deployment and operational costs. Second we know spectrum is limited resource and it cannot be increased above the available limit, also when going for higher frequencies (above 5Ghz) the propagation loss also increases. These were the methods followed so far for increasing the throughput. The third option of increasing spectral efficiency has not been used for large improvements in the past but it can be the driving force in future 5G networks. Spectral efficiency of a point-to-point wireless transmission is governed by the Shannon's capacity limit C given in Eqn. (1) and it cannot do much improvement by increasing the signal power because a capacity increase from 4 bits/s/Hz/user to 8 bits/s/Hz/user requires an increase of signal power by a factor of 17.

$$\mathrm{C} = \log_2\left(1 + \frac{\text{Receieved signal power}}{\text{Interference power} + \text{Noise power}}\right) \quad [\text{bit/s/Hz/User}] \tag{1}$$

Another way to increase the SE is to provide many parallel simultaneous transmissions as shown in Fig.1, where instead of using a single Omni directional beam to serve all the users, multi antenna transmission and beam-forming techniques are used to form spatially focussed beams to each desired user.

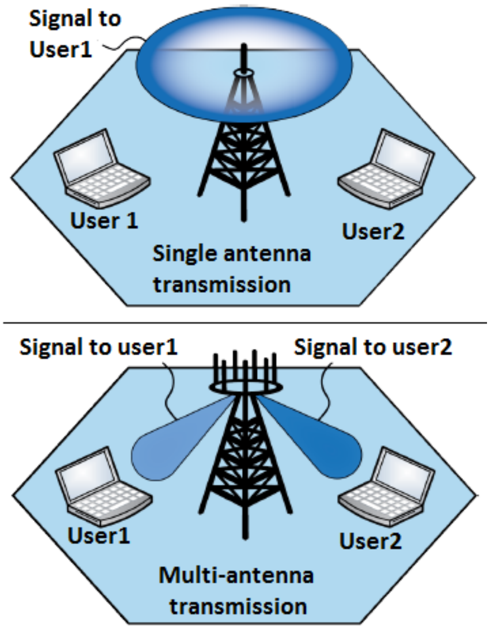


Fig.1 Single antenna and Multi-antenna transmission

On extending the above technology to Multi-Cell Multi-User MIMO with base stations carrying M antennas with active parallel uplink/downlink K number of users gives an increase in spectral efficiency roughly proportional to the minimum of (M,K and S/2) where S is the channel coherence block length. So the spectral efficiency can easily be doubled by doubling the number of base station antennas (M) or by doubling the number of active users(K) per cell. But in this MU-MIMO technology interference, the difficulty to learn users channels and the difficulty to coordinate the base stations were the limiting factors for the SE improvement above a limit. Taking this MU-MIMO to the new technological level of Massive MIMO which uses large number of base station antennas of the order of few 100s to 1000 can have very narrow beam-forming with little interference leakage. It eliminates all the drawbacks of MU-MIMO and gives very large increase in the spectral efficiency.

The downlink data transmission system model used for the simulation is shown in Fig.2. Here each antenna is supplied with sum of information symbols intended for each of the users. Antenna-1 multiplies the signal x_1 intended for user-1with the conjugate of the estimated channel (h^*_{11}) and each of the antenna does the same thing. Hence all of the signals in tailing x_1 arrives in phase at user-1 and hence the amplitude of beam-forming gain goes with antenna M and they tend to arrive at out of phase at the other users and hence their amplitude goes as the square root of them. It uses the simplest possible precoding and beam-forming technique, which is zero forcing but it is very effective.

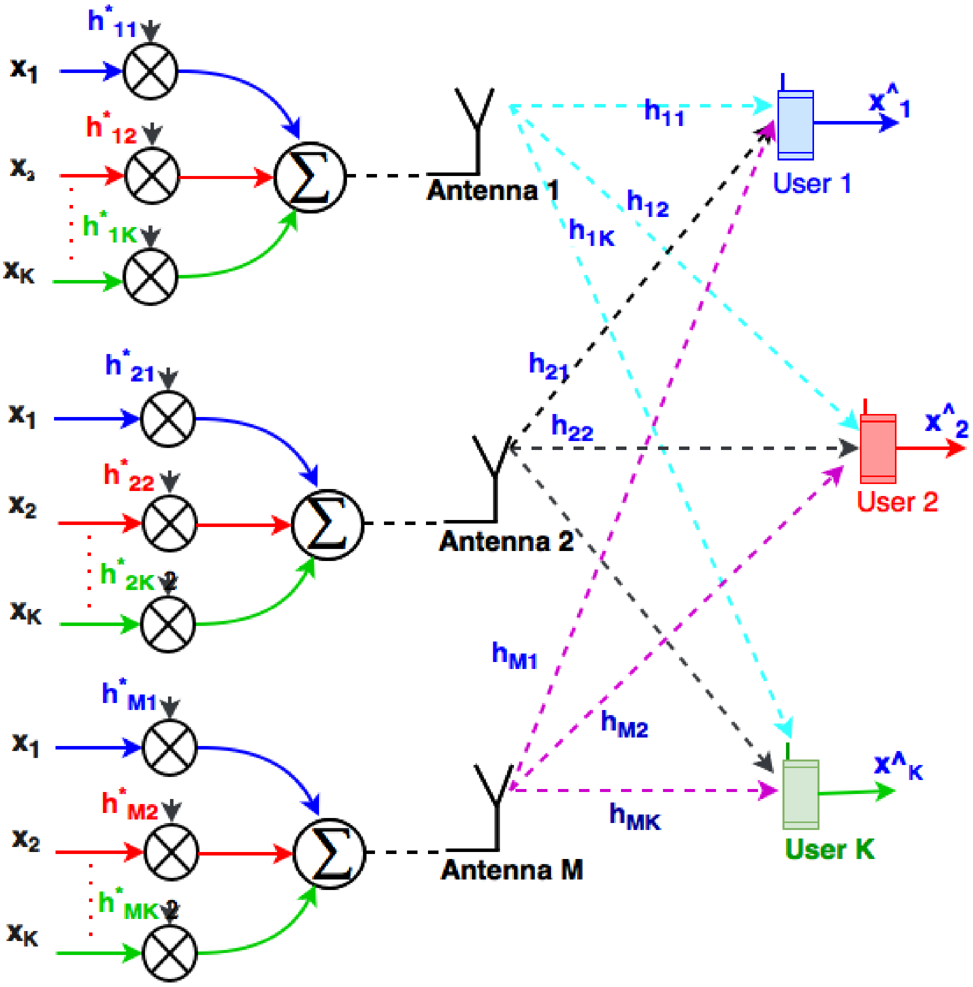


Fig. 2. Downlink data transmission

In the uplink data transmission shown in Fig.3, signals from different users are collected by the antenna and then individually multiplied by the conjugate of the channel estimate and then it is added with the corresponding multiplier outputs from the other antennas to get the desired signal. The uplink signal received at the BS $_j$ in a particular frame is given by

$$y_j = \sum_{l=1}^{L} \sum_{k=1}^{K} \sqrt{p_{lk}} h_{jlk} x_{lk} + n_j \tag{2}$$

Where L is the number of cells, K is the number of users, X_{lk} is the symbol transmitted by the k^{th} user in the l^{th} cell and p_{lk} is the transmit power, h_{jlk} denotes the channel response between the j^{th} BS and k_{th} UE in the l^{th} cell in a given frame and n_j is the additive noise component.

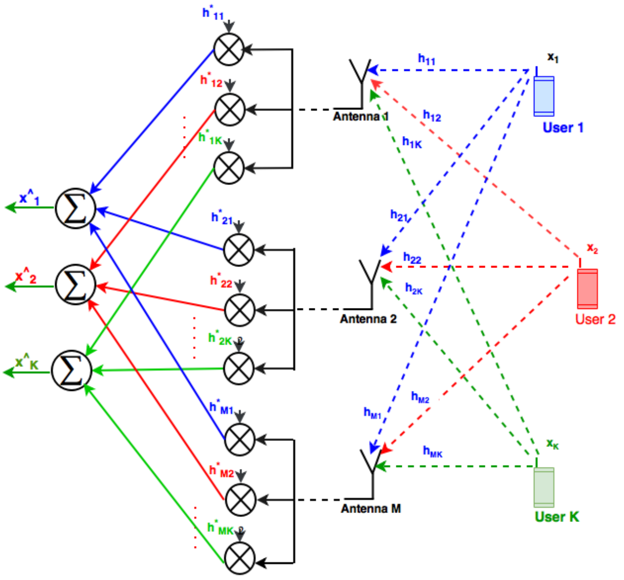


Fig. 3. Uplink data transmission

The received signal on the downlink by the kth user at the jth cell is given by

$$Z_{jk} = \sum_{l=1}^{L} \sum_{k=1}^{K} h_{ljk}^{T} w_{lm} S_{lm} + n_{jk} \tag{3}$$

Where h^T is the transpose of the channel response h, s_{lm} is the symbol meant for mth user in lth cell, w_{lm} is the precoding vector and n_{jk} is the additive noise.

The theoretical maximum of the attainable uplink and downlink spectral efficiencies are given by the equations.

$$SE_{UL} = \partial^{UL}\left(1-\frac{B}{S}\right)\mathbb{E}_{(x)}\{\log_2(1+SINR_{jk}^{(UL)})\} \quad [bits/s/Hz] \tag{4}$$

$$SE_{DL} = \partial^{DL}\left(1-\frac{B}{S}\right)\mathbb{E}_{(x)}\{\log_2(1+SINR_{jk}^{(DL)})\} \quad [bits/s/Hz] \tag{5}$$

The spectral efficiency expressions for the uplink and downlink are almost identical, only the uplink and downlink fractions differ. $\mathbb{E}_{(x)}$ is the expectation of the UE positions and SINR is the effective signal-to-interference-and-noise ratio. Now when we consider the number users K per cell the SE expressions per cell for uplink and downlink can be expressed as

$$SE_j^{UL} = K\partial^{(UL)}\left(1-\frac{B}{S}\right)\log_2(1+1/I_j) \quad \text{[bits/s/Hz/cell]} \tag{6}$$

$$SE_j^{DL} = K\partial^{(DL)}\left(1-\frac{B}{S}\right)\log_2(1+1/I_j) \quad \text{[bits/s/Hz/cell]} \tag{7}$$

Where SEj represents the SE of the jth cell, B is the number of symbols in a data frame, S is the coherence block length and Ij represents the interference. The next consideration that has to be taken is the finite and asymptotic analysis. Here we assume that the uplink fraction and downlink fraction give a sum of 1. i.e $\partial^{(DL)} + \partial^{(UL)} = 1,$ then the SE can be expressed as

$$SE_j = K\left(1 - \frac{B}{S}\right)\log_2(1 + 1/I_j)[\mathrm{bits/s/Hz/cell}] \tag{8}$$

This makes the analysis much easier because the final spectral efficiency equation that we arrived at is independent of two actors $\partial^{(DL)} and \partial^{(UL)}$, the uplink and downlink fractions. This permits us to analyze and optimize the spectral efficiency of the communication system as a whole without considering the downlink and uplink separately.

A. Model Characteristics

In this work we have considered following characteristics for the massive MIMO wireless model Amplify and forward relaying scheme: Basically it sends an amplified version of the received signal in the last time slot and compared with the other relaying scheme such as decode and forward. This scheme requires very much less computing power and incurs very less delay.

Dual hop transmission system: Each of the hop is dependent on each other.

Full Duplex communication Wireless full duplex system allows simultaneously transmitting and receiving signals over a single channel. The uplink and downlink channel transmitter and receiver function independently.

TDD scheme of communication: In time division duplex communication links different time slots in same frequency band are allocated for the uplink and downlink channels as per the network load requirements.

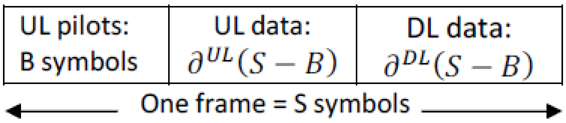
Number of BS antennas and users: Base station has M number of Transceiver antennas and supports K number of active users in each cell.

Noise variance $\sigma_R^2 = \sigma_D^2$*:* Noise is purely random and has zero mean, noise power is equal to its variance. Here noise variance at the receiver and the destination is assumed to be the same.

The signal to noise ratio(SNR) : SNR which is the measure of signal power to the background noise power is assumed to be ranging from 0 dB to 5 dB.

Channel Estimation using pilot signals: Channel estimation is the technique to measure the characteristics of a wireless channel and an easy method to do this is by comparing known transmitted (pilot) signals and the received signals. Since we have only limited number of orthogonal sequences to be used as pilots they have to be reused in adjacent cells and this similar adjacent cell pilot orthogonal signal interfere with each other and cause pilot contamination. It can be reduced to some extent by using specialised filters in which it helps to randomise the sequence numbers and thus suppress the pilot contamination.

Frame structure : A total number of 'S' symbols are transmitted in a frame, out of which 'B' is the number of symbols used for pilot transmission. From the remaining (S-B) symbols $\partial^{DL}(S-B)$symbols areused for downlink and $\partial^{UL}(S-B)$symbols are used for uplink$\partial^{DL}$and$\partial^{UL}$are the fractions for downlink and uplink transmission. Details are shown in Fig.4



UL pilots: B symbols	UL data: $\partial^{UL}(S-B)$	DL data: $\partial^{DL}(S-B)$

One frame = S symbols

Fig. 4. Frame structure

Coherence time is, the time duration over which the impulse response of the channel remains constant, taken as Tc seconds. Coherence bandwidth is, the range of frequencies in which the channel is assumed as flat, taken as Wc Hz. Then block length S=WcTc symbols, we set S= 400 (eg: 200kHz coherence bandwidth and 2ms coherence time).

Pilot reuse factor: It is the number of cells in a cluster in which the same pilot sequence is used . Pilot reuse factor $\beta = B/K \geq 1$: B is the number of symbols in a frame used for pilot transmission and K is the number of users. Value of β is overall considered as greater than one.

Precoding algorithm : Precoding is a technique where transmitter send information coded according to the pre-knowledge of the channel. Here the conventional linear precoding schemes Zero Forcing and Maximal Ratio Combining are used

RESULTS AND DISCUSSIONS

A simulation model with the above said characteristics has been set up using matlab to evaluate the SE performance of the Massive MIMO antenna system. The effect of various parameters like number of BS antennas, coherence block length, number of active users and different precoding algorithms on SE is studied and results are analysed.

In Fig. 5 variation of the SE is plotted against the number of BS antennas ranging from 10 to 1000 keeping the number of active UEs (K) in each cell as constant. The simulation is repeated for a wide range of active UEs from 2 to 40.The simple linear precoding technique, zero forcing is used for the above simulation. From simulation results it can be inferred that the SE increases abruptly with the number of BS antennas at the beginning and later it becomes almost saturated. With less number of users SE reaches its maximum with less number of BS antennas because only less number of spatially diverse beams are required to serve all the UEs and also there is no need for very narrow beam shaping. When we compare the SE plot for K=30 and K=40 at the initial portion where the number of BS antennas are less, K=30gives better spectral efficiency than K=40. This is because in this region the number of BS antennas is not sufficient to provide the necessary beam-forming and spatial diversity required for the large number of users.

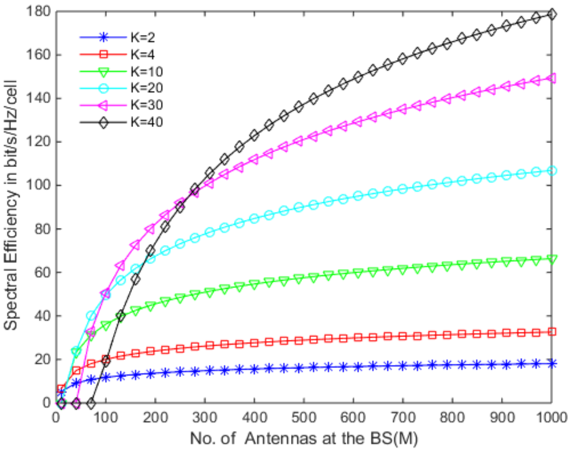


Fig. 5. SE per cell versus M for different values of K

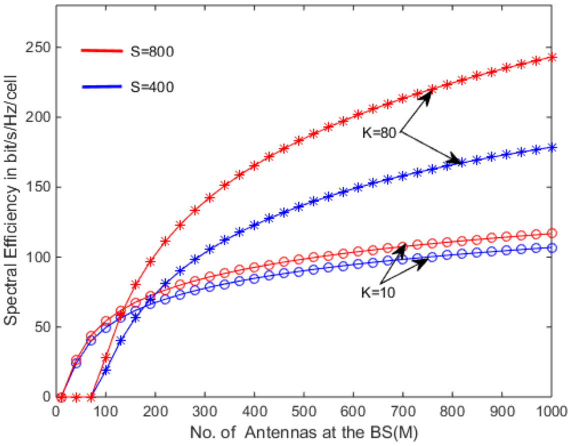


Fig. 6. Impact of coherence length(S) on SE

Fig. 6 gives the effect of coherence block length (S) on the per cell SE. Massive MIMO can schedule more number of UEs when the value of coherence block length is high and that will give good improvement in SE when both the coherence block length and number of UEs are large. When K=10 system has to schedule only less number of UEs and most of that will be successful even when the coherence length is 400 and an increase to 800 will not give considerable improvement in SE, whereas the SE improvement is very high in K=80, for the same increase of S from 400 to 800. In Fig. 7 we analyse the potential of SE under two different precoding techniques Zero-Forcing and Maximum Ratio Combining. Excessive number of base station antennas compared with the number of users makes the simple linear signal processing techniques works to nearly optimal in massive MIMO systems [1]. Hence in this plot we can find for both ZF and MRC the SE increases in the same manner with an increase in the number of BS antennas. With MRC precoding the BS tries to maximise the received SNR ignoring the effect of multiuser interference whereas

ZF receivers take the inter user interference in to consideration and neglect the effect of noise. Hence ZF always outperforms MRC and gives better SE for all values of K as well as M.

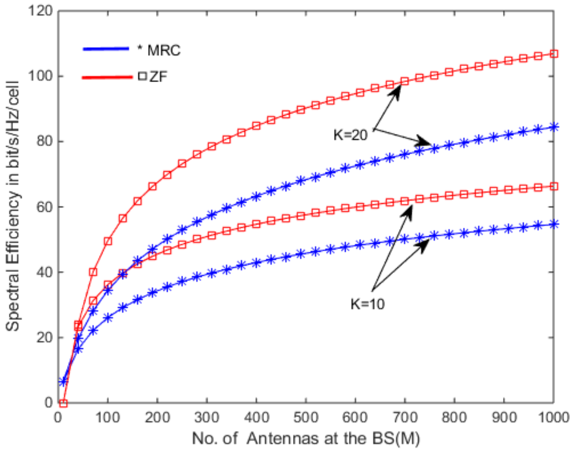


Fig. 7. Impact of precoding techniques ZF and MRC on SE

In Fig. 8 variation of the SE is shown against the number of UEs keeping the number of BS antennas as constant. Consider the red coloured plot with M=100, where SE increases with an increase in K and reaches the maximum value of 54 when K becomes 30 and then reduces gradually and reaches zero for a value of K equal to 100. It shows that 30 is the optimum number of users that can be served with 100 number of BS antennas, trying to serve more number users will make the available number of BS antennas insufficient to form the necessary spatial diversity and beam-forming. Doubling M from 100 to 200 rises and optimum K from 4 to 82.

Finally in Fig. 9 optimum value of UEs for different coherent block lengths (S) is plotted against varying number of BS antennas. Value of S depends mainly on mobility of the user, frequency of operation and propagation environment. The CSI acquisition is limited by the channel coherence and how this impacts SEs is shown in the above graph. It is understood from this graph that the coherence block length limits the maximum number of active users in a single cell. Doubling the value of S from 200 to 400 gives an increase in K from 90 to 180

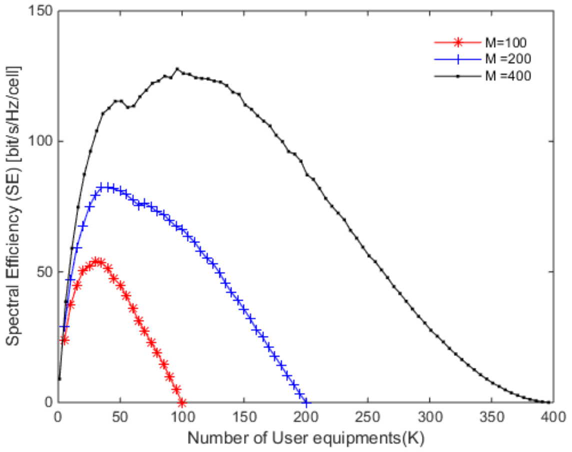


Fig. 8. SE per cell versus K for different M

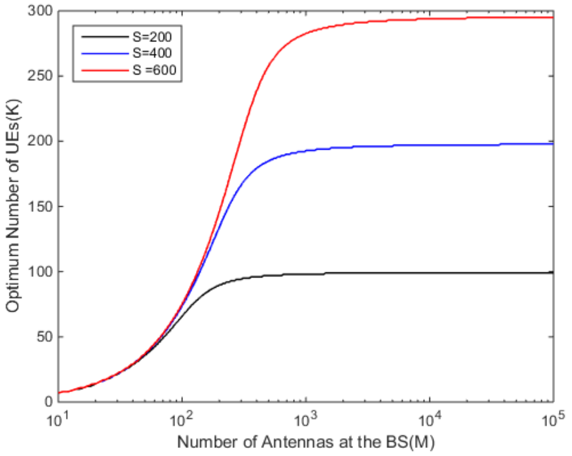


Fig. 9. Optimum value of K versus M for different values of S

CONCLUSION

In this paper a Massive-MIMO system with TDD architecture is designed and different methods to maximise its SE are well examined. The effect of the number of active users in a cell, length of coherence block, number of base station antennas and different linear precoding methods on the spectral efficiency are evaluated through simulation. From the results it is inferred that high SE per cell is attained by simultaneously scheduling more number of UEs for transmission. Within the available spectrum Massive MIMO can schedule more UEs with larger coherence block lengths and also SE performance increases with increase in the number of BS antennas. ZF precoding is the better option in terms of maximizing the SE and also its implementation is very simple. Results also reveal that a massive MIMO with 100 BS antennas can easily achieve a SE much more than 10 times the IMT-Advanced requirement of 3 bit/s/Hz/cell [49] and BS with larger antenna arrays of 400 elements can go above 40 times the IMT requirement. In this work it is assumed that the cells are symmetric as well as the users in the cell are uniformly distributed which is not the case in any practical system. Considering these issues also in the study may require extensive monte-carlo simulations and is an interesting possibility for future work.

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