International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075 (Online), Volume-9 Issue-4, February 2020

Achievable Capacity with Spatial Channel Correlation in Massive MIMO Multi-Cell Systems

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Abstract: ***Massive Multi-Input and Multi-Output (MIMO) antenna system provides unlimited capacity by the spatial multiplexing and array gain. Since the data rate has been limited by the coherence interference due to pilot contamination (PC). In this paper, we propose transmit combine and precoding schemes to achieve asymptotic capacity in multi-cell scenario, when the number of base station antennas tends to infinity. The impact of spatial channel correlation on channel capacity is explored by considering the co-variance matrices of the user –terminals (UT)s .To do this, we presented linear processing schemes such as MMSE,MRC, and ZF.Where MMSE achieves high capacity in the presence of large-scale fading and PC. Since the diagonals of the channel covariance matrices were designed with non- zero Eigen values and linearly independent. The results outperform and obtain asymptotic limit, when the co-variance of UTs are linearly independent. The results were simulated by using MATLAB 2018b.***

Index Terms: ***channel capacity, Spatial Channel Correlation, Multi input and multi output, Multi-cell.***

I. INTRODUCTION

This Shannon capacity demonstrates the maximum achievable data rate of a channel with given bandwidth and desired signal to noise ratio. Future wireless networks demands high speed transmission and serve large number of user terminal(UT)s. Massive Multi-Input and Multi-Output (MIMO) is considered as a suitable candidate to obtain higher Spectral efficiency(SE) by spatial multiplexing of massive number of UTs in multi-cell scenario [1-5]. This is achieved by deploying massive number of antennas at the base station (BS). The signals are coherently combined by using channel estimates with pilot signaling in the uplink (UL), where the noise and interference are less than the desired UT signal power. It is possible with the large value of BS antennas and time division duplexing (TDD). Similarly, the signals are transmitted with precoding in the downlink (DL), where the channels are estimated by using channel reciprocity principle.

The channel coherence time limits the pilot resources, it leads to recommend reusing of same pilot signals in different cells. This process provides the PC, which generates two major issues: firstly, the desired UT channel estimate is correlated with other UTs estimate, since reusing of same pilots in other cells. Secondly, the channel capacity degrades with the PC. Therefore, it is not possible to eliminate the PC completely. In this paper, we demonstrate how to improve the channel capacity in the presence of the PC and noise. The impact of PC on SE is well manifest by Marzetta in [6], when the number of antennas reaches to infinite at the BS.

In this paper, we presented linear receive combing and transmit precoding schemes for SE analysis in massive MIMO systems. We proposed different schemes, such as multi-cell minimum mean square error (M-MMSE), single –cell minimum mean square error (S-MMSE), ZF (zero forcing) and MR (maximum ratio).In M-MMSE method ,the channels of UTs were estimated from all the cells. While the S-MMSE scheme estimates only the UTs of own cell. The effect of spatial channel correlation on channel capacity was explained with two consequences: firstly, the channels were considered as spatially correlated fading and the covariance matrices were rank deficient. Secondly, the channels were assumed as independently and identically distributed (i.i.d) by Rayleigh fading with no spatial channel correlation. It is treated as a special case of spatial channel correlation. In both cases, there is a finite limit on SE when the BS antennas tend to infinity. Several categories were reported in the literature for the evaluation of PC [7], which is also referred as pilot decontamination. Firstly, the pilot signals were allocated to the UTs by the BS with different support of covariance matrices. But, this method can reduce the interference with finite limit. Secondly, semi-blind channel estimation techniques were reported [8] to mitigate the PC by spatially separating the desired UTs from the undesired UTs. This method requires that the knowledge of channel coherence time and the BS antennas tend to infinity, which is not feasible in real time application of networks. The third category allocates the different pilot sequences and multiple pilot phases to the UTs, which is not required any statistical information. This scheme is more effective when the number of UTs less than or equal to the total pilot length. This method allocates the orthogonal pilot sequences to the UTs to mitigate the PC problem. In practice, this is not a suitable solution to mitigate PC in multi-cell networks. Finally, the PC precoding [9] achieves an unbound SE by joint coherent receiving/transmission, which can reduce PC by rejecting the interference from UTs in other cells.

Revised Manuscript Received on February 28, 2020.
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The main contribution of this work was summarized as follows, In this paper, we answered how to achieve the unlimited capacity in the presence of PC. To gain high SE, massive .antennas should be deployed at the BS.

We analyzed the capacity in massive MIMO for both single and multi-cell systems.

We proposed linear combing/transmit precoding schemes for SE analysis such as MMSE, ZF, and MRC by considering Rayleigh fading channels. Here, the capacity is considered based on covariance matrices variation. The maximal SE is achieved when the precoding/combining scheme as MMSE, where the UTs were assigned with independent pilot sequences and covariance matrices.

We also address the issue of multi-cell cooperation in massive MIMO, no prior work have highlighted the impact of covariance of channel matrices on the capacity. These schemes manifest achieving unlimited SE in the presence of PC. The results were calculated for both UL and DL with two UTs perspective.

The organization of this paper was demonstrated follows as; the proposed system is presented in Section II. The SE analysis was structured in section III for both UL and DL. The results and discussions were demonstrated with varying antennas at the BS versus SE in section III. Finally, the conclusion is presented. $E\{.\}$ and $[.]^T$ denotes expectation and transpose. Where $F_{\mathbb{C}}(0, C)$ describes the circularly symmetric complex Gaussian distribution with mean zero and variance equal to covariance matrix C.

II. PROPOSED SYSTEM MODEL

In this section, the proposed multi-cell massive MIMO system model is presented in fig.1. Here, we considered two UTs in each cell and which are distributed as Poisson point process (PPP). The BS antennas are denoted by M, and UTs with K.

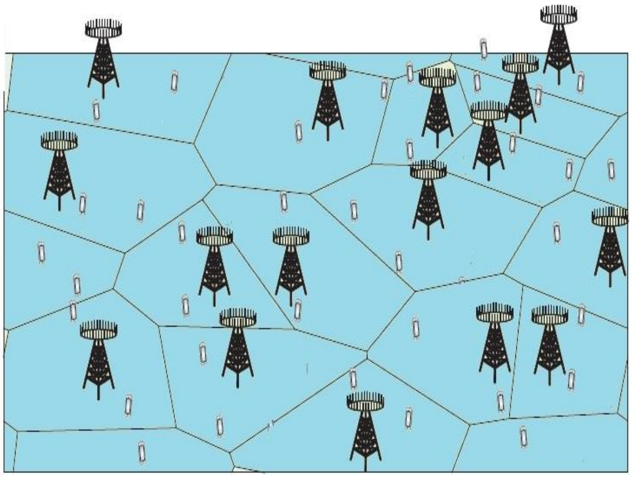

Fig 1.Proposed multi-cell Massive MIMO system

A. Uplink Channel Estimation

In the UL channel estimation, the UTs and BSs are strongly synchronized by using the TDD technique. The pilot estimation process is followed by the data transmission stage at the BS. The proposed frame structure is presented in Fig.2 with UL and DL. The two UTs are allocated with the same sequence of pilot length τ_p.which is denoted by a symbol $\emptyset_p$. here a portion of the time is allocated for UL channel estimation. The data is transmitted in the UL by using $S_c - \emptyset_p$ symbols where S_c denotes the length of the coherence block. The BS uses the UL pilot s for data transmission in the DL by using channel reciprocity [10]. The DL data transmission phase is achieved by precoding scheme at the BS. The length of the DL is equal to $S_c - \emptyset_p$ for data transmission phase. It is true that the elements of $\emptyset_p$ are given by condition, $\|\emptyset_p\|^2 = {\emptyset_p}^H \emptyset_p$=1.

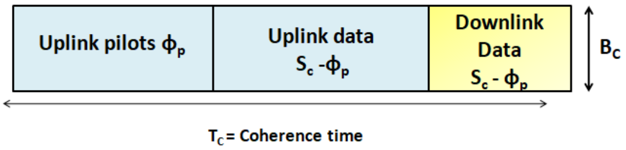

Fig.2 Proposed frame structure

The UL received signal at the BS is represented as follows,

$$Y_{pt} = \sqrt{\rho_t}\ g_1 {\emptyset_p}^T + \sqrt{\rho_t}\ g_2 {\emptyset_p}^T + N \quad (1)$$

Where N is the normalized noise power and ρ_t is normalized pilot power. The channels g_1 and g_2 are estimated by the received matrix Y_{pt}. The channel estimation with MMSE scheme [9] is given by

$$\widehat{g_k} = \frac{1}{\sqrt{\rho_t}} C_k D^{-1} Y_{pt} {\emptyset_p}^* \quad (2)$$

Where $D = \frac{1}{\sqrt{\rho_t}} \mathrm{E}\{Y_{pt}\emptyset_p (Y_{pt}\emptyset_p)^H\} = C_1 + C_2 + \frac{1}{\rho_t} \mathrm{I}_M$

The channel estimates are calculated by using Eq. (2), where the matrix D is inverted and multiplied with the received signal Y_{pt} followed by pilot sequence ${\emptyset_p}^*$. The channel estimate is being a function of covariance matrix. The impact of spatial channel correlation among the channels will lead to decrease the channel capacity [11, 12]. It is observed that the correlation between the UTs should be minimum to improve SE in a cell. The estimation error in the MMSE scheme [13] is presented as follows,

$$g_e = g_k - \widehat{g_k} \quad (3)$$

The desired channel g_k and estimated channel $\widehat{g_k}$ are distributed with zero mean and variance equal to $\emptyset_p$: $F_{\mathbb{C}}(0, \emptyset_p)$. The channels $\widehat{g_1}$ and $\widehat{g_2}$ are computed from Eq. (3) by substituting $k = 1,2$. The spatial channel correlation among the UTs is presented with correlation matrix [14] as follows,

$$R_{12} = \mathrm{E}\{\widehat{g_1}\ \widehat{g_2}\} = C_1 D^{-1} C_2 \quad (4)$$

Where channel estimate $\widehat{g_2}$ is scaled by constant β that is $\widehat{g_1} = \beta\ \widehat{g_2}$. This is considered as the high spatial correlation between the two channel estimates.

III. CAPACITY ENHANCEMENT

In this section, we addressed the issue of improving channel capacity related to the SE. The data rate of cellular network per unit area is defined as follows,

$$R = Cell\ density \times B \times SE \quad (5)$$

Where R denotes the throughput and B refers to available spectrum in the system design. The channel capacity is directly proportional to cell density, available bandwidth and SE of the network. It is identified that the higher the cell density will reduce size of the cell and coverage. But the total system is increased since more number of cells is required.

Similarly, available bandwidth is a scarce resource and spectrally limited. The alternate solution is to improve the SE, which leads improve channel capacity.
In this paper, we mainly concentrated on enhancement of system throughput by deploying massive antennas at the BS with linear schemes.

A. Uplink data transmission

The data transmission phase requires the pilot signals from the UL channel estimation [15]. The SE of the proposed system in the UL is being a function of signal to interference plus noise ratio (SINR). The asymptotic limit of SE is achieved by considering antennas at the BS equal to $M \to \infty$. The SE is computed in the UL by using the following equation as,

$$SE_{UL} = (1 - \tau_{OH})\mathrm{E}\left[\log_2\left(1 + \gamma_{\mathrm{UL}}\right)\right] \qquad (6)$$

Where $\tau_{OH} = \frac{\tau_p}{\tau_c}$

The SNR is expressed in the UL with channel estimates as follows,

$$\gamma_{\mathrm{UL}} = \frac{\left|w^H\ \widehat{g_1}\right|^2}{\mathrm{E}\left[\left|w^H\ \widehat{g_1}\right|^2 + \left|w^H g_2\right|^2 + \frac{1}{\rho_{UL}} w^H w \middle|\ \widehat{g_1}, w^H\right]} \qquad (7)$$

$$= \frac{\left|w^H\ \widehat{g_1}\right|^2}{w^H\left(\ \widehat{g_2}\ \widehat{g_2}^H + P\right)w}$$

Where $P = \sum_{k=1}^{2}\left(C_k - \emptyset_p\right)\emptyset_p + \frac{1}{\rho_{UL}}\mathrm{I}_M$

The SNR is maximized by the condition as,

$$w = \left(\sum_{k=1}^{2}\ \widehat{g_k}\ \widehat{g_k}^H + P\right)^{-1}\ \widehat{g_1} \qquad (8)$$

The desired SNR in the UL to minimize mean

$$\gamma_{\mathrm{UL}} = \ \widehat{g_1}^H\left(\ \widehat{g_k}\ \widehat{g_k}^H + P\right)^{-1}\ \widehat{g_1} \qquad (9)$$

B. Down link data transmission

The data transmission in the DL uses UL pilot signals which is obtained by using channel reciprocity as,

$$X = \sqrt{\rho_{dl}}g_1 w_1 s_1 + \sqrt{\rho_t}\ g_2 w_2 s_2 \qquad (10)$$

$$\mathrm{E}\left\{\mathrm{w}_{\mathrm{k}}^2 s_2\right\} = \ \rho_{\mathrm{dl}} \qquad (11)$$

$$SE_{DL} = (1 - \tau_{OH})\mathrm{E}\left[\log_2\left(1 + \gamma_{\mathrm{DL}}\right)\right] \qquad (12)$$

where

$$\gamma_{\mathrm{DL}} = \frac{\left|g_1^H w_1\right|^2}{\mathrm{E}\left[\left|g_2^H w\right|^2 + V\left|g_1^H w_1\right|^2 + \frac{1}{\rho_{UL}}\right]}$$

The unlimited SE is achieved asymptotically under PC. Here, both channel estimates $\widehat{g_1}$ and $\widehat{g_2}$ are considered as linearly independent. Similarly, the precoding vectors are assumed as linearly independent, to do this ,the precoding vector $p_1$is orthogonal to the channel estimate g_2. This is true for interchanging the variables given as follows,

$$w_1\widehat{g_2} = 0\ , \text{ and } \quad w_2\widehat{g_1} = 0 \qquad (13)$$

C. Zero-forcing

The channel estimate in ZF scheme is implemented with covariance matrix [16] as follows,

$$\widehat{g_k} = C_K \frac{1}{\sqrt{\rho_t}} D^{-1} Y_{pt} \emptyset_p{}^* \qquad (14)$$

Where $\frac{1}{\sqrt{\rho_t}} D^{-1} Y_{pt} \emptyset_p{}^* = I_M$

The precoding vector w_1 is orthogonal to channel estimate $\widehat{g_2}$ and maximum (non-orthogonal) to $\widehat{g_1}$ presented as,

$$w_1^H\widehat{g_2} = 0 \quad \text{and} \quad w_1^H\widehat{g_1} = 1 \qquad (15)$$

Where $g_1 = c_1 I_M$ and $\widehat{g_2} = c_2 I_M$

The precoding (combining) vectors related to channel matrix is given by

$$[w_1\ \ w_2\ ] = \hat{G}[G^H G] \qquad (16)$$

The calculation of G from the channel estimates should be linearly independent [17, 18] and satisfies the condition given by (17).The maximum SE is achieved, when SINR in the UL is equal to the SINR in the DL. The effective SINR is presented in the UL as follows,

$$\gamma_{\mathrm{UL}} = \frac{\left|w^H\ \widehat{g_1}\right|^2}{\left[\left|w^H\ \widehat{g_2}\right|^2 + \sum_{k=1}^{2} w^H\left(C_k - \emptyset_{pk}{}^*\right)w + \|w\|^2\right]} \qquad (17)$$

The covariance matrices are to be designed linearly independent to obtain maximum SE [19-21]. To do this, both MMSE and ZF schemes are implemented linearly independent to achieve maximum SE.

D. Element wise-Minimum mean square error estimation

The low SE in the UL is achieved by using element wise -Minimum mean square error (EW-MMSE). Here, the BS does not knowledge of CSI of co-variance matrix. In this method, each element of the channel is estimated separately by ignoring the spatial channel correlation between the elements of the array. This scheme is designed only the diagonal elements of the co-variance matrix. The channel estimate of EW-MMSE [22] is given by

$$\hat{h}_k = \frac{1}{\sqrt{\rho_t}} \frac{[C_k]}{\left[[C_1] + [C_2] + \frac{1}{\rho_t}\right]} Y_{pt} \emptyset_p{}^* \qquad (18)$$

IV. SIMULATION RESULTS AND DISCUSSION

In this section, the simulation results were demonstrated by using MATLAB 2018b.The reported results explains that how to achieve maximal SE under the presence of high PC. We considered cells with $L = 4$, number of UTs per cell $K = 4$. The parameters were presented in Table.1 for simulation. Here, the total geographical area of the cell has been divided in to four corners. The antennas were deployed at each corner of the BS. The UTs were distributed under worst case condition and located at the cell edge. Thus, this setup would generate strong PC since the UTs share the same pilot. It is observed that the SE is improved by increasing the effective SINR. Since large value of M gains high SINR. The ZF scheme achieves poor SE by suppressing total interference which removes a portion of the signal. Interestingly, the MMSE provides higher SE [25].

Since MMSE mitigates the interference by coordinating the received combining this leads to provide superior SE than the other schemes.

Table- I: Simulation Parameters

S.No	Propagation Parameters	
	parameters	***Value***
1	Coherence block length	200
2	Path-loss exponent	3.76
3	Bandwidth	$20e^6$
4	UL power	1 WATT
5	Noise Figure	10
6	DL power	0.1 WATT

We consider time splitting technique to compare other schemes which is assumed as the reference curve with other schemes. Here, the cells are active in the coherence block. We presented Rayleigh fading channel model with large channel variations. Firstly, we simulated the SE for UL with M=1000, and ρ is ranging from 0.5 to 0.7. Here ρ plays prominent role to achieve the higher capacity. Fig.3 (a) illustrates how SE varies with BS antennas with different combining schemes and ρ equal to 0.7. the maximum SE of 2.4 bits/Hz/UT is achieved with MMSE scheme. This model is implemented with log-normal fading with small variations in the channel. We noticed that MMSE achieves higher SE without any bound.

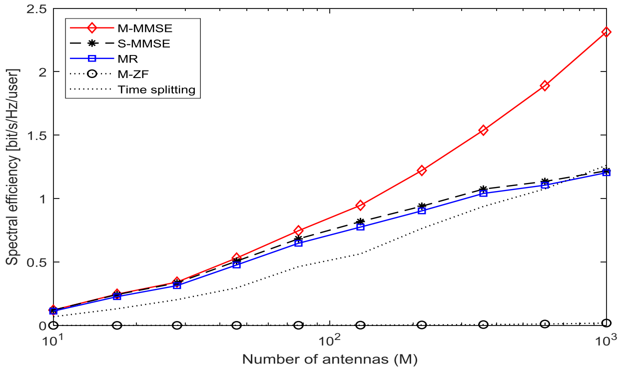

Fig.3.(a) SE in (bits/Hz/UT) Vs number of BS antennas with correlation coefficient ($\rho = 0.6$)

Fig.3 (b) shows SE with $\rho = 0.6$ and number of antennas at the BS equal to 1000.the MRC follows the S-MMSE and obtains with SE of 1.6 bits/Hz/UT. The time spitting is used as reference curve to compare the remaining schemes and achieves lower SE of 1.3 bits/Hz/UT .

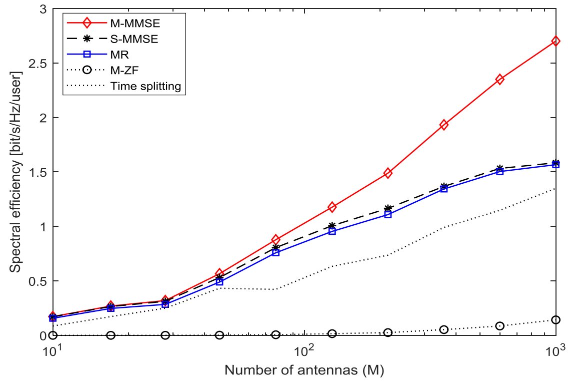

Fig.3. (b) SE in (bits/Hz/UT) Vs number of BS antennas with correlation coefficient ($\rho = 0.6$)

Fig.3(c) obtains higher SE of 3.2 bits/Hz/UT by using M-MMSE scheme with $\rho = 0.5$ .The MRC scheme is approaching S-MMSE when the antennas at the BS more than 100. Both the schemes achieve equal SE of 2.4 bits/Hz/UT. The ZF schemes obtains poor SE of 1.4 bits/Hz/UT since M-ZF does not eliminate the interference completely. We observed that the spatial correlation among the channels shows a strong impact on SE. The SE is increased by decreasing the correlation coefficient from 0.7 to 0.5.

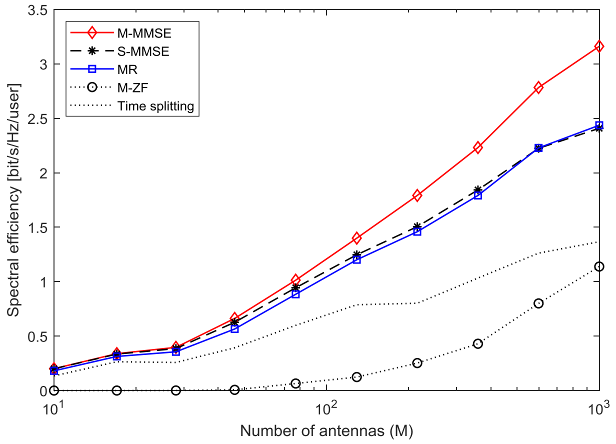

Fig.3.(c) SE in (bits/Hz/UT) Vs number of BS antennas with correlation coefficient ($\rho = 0.5$)

Fig.4 illustrates SE changes with standard deviation of fading variations over the array. We considered the σ equal to 6. Here, spatial correlation plays an important role to select the receive combining scheme. Fig.4 illustrates how SE varies with BS antennas with different combining schemes. It is noticed that S-MMSE and MRC Schemes were highly affected by the interference generated from the UTs. Since UTs were allocated with same pilot, which improves interference provided by the PC. The S-MMSE achieves the SE of 3 bits/Hz/UT and MRC of 2.8 bits/Hz/UT. Interestingly, the M- MMSE schemes mitigate interference than the other schemes. It obtains the SE of 4 bits/Hz/UT with σ equal to 5. All these schemes receive same level of interference from the other UTs.

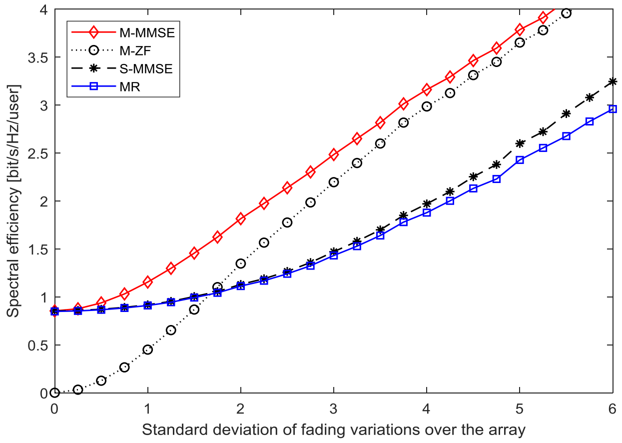

Fig.4. SE (bits/Hz/UT) Vs standard deviation of fading variations over the array

The covariance matrices are considered as the linearly dependent [23]. It is noted that M-MMSE scheme results high SE by using the large scale fading model with small variations. The MMSE obtains superior SE gain over MRC, S-MMSE and M-ZF. Since the covariance matrices are linearly independent. When large variations are considered in the channel, the ZF scheme tends to reach M-MMSE. However the M-ZF is not better than M-MMSE since the MMSE is optimal when massive antennas are deployed at the BS. We compared mthe simulation results with the results of [23, 24] with σ equal to 0.4 with large scale variations. It is noticed that the reported results outperform than the results of [23, 24].

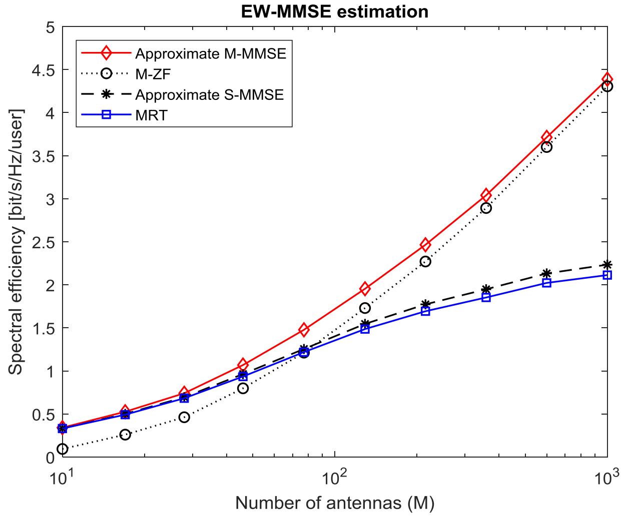

Fig.5. SE in (bits/Hz/UT) Vs number of BS antennas with EW-MMSE estimation

Fig.6 shows the SE by considering the diagonal elements of co-variance matrix. We noticed the following observations, firstly, M-ZF scheme is approaching M-MMSE for higher value of M. secondly, S-MMSE and MRC schemes provide the similar SE with finite limit. There is smaller difference in the obtained SE in the range of 1% to 3% .which is negligible by considering closed co-variance matrices. It is shown in Fig.6 that the SE in the DL is also equal to the SE in the UL.

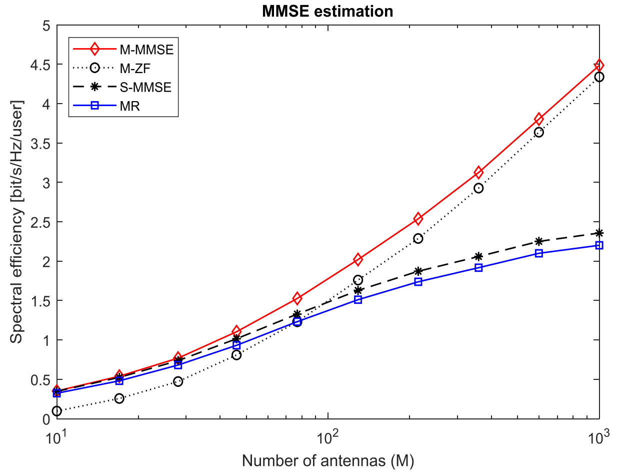

Fig.6. SE in (bits/Hz/UT) Vs number of BS antennas with MMSE estimation

Fig.7 illustrates how received power over the noise varies with different scenarios such as desired signal power, measuring the interference from UT using same pilot and different pilot. It is designed with σ =6.It is noticed that S-MMSE and MRC Schemes were highly affected by the interference generated from the UTs. Since UTs were allocated with the same pilot. These schemes improve the interference provided by the PC. Interestingly, the M- MMSE schemes mitigate interference than the other schemes .These schemes receive same level of interference from the other UTs. We noticed the following observations from Fig.7.Firstly, our simulation results outperform than the results of [23, 24] with M=300 and number of UTs equal to 10.

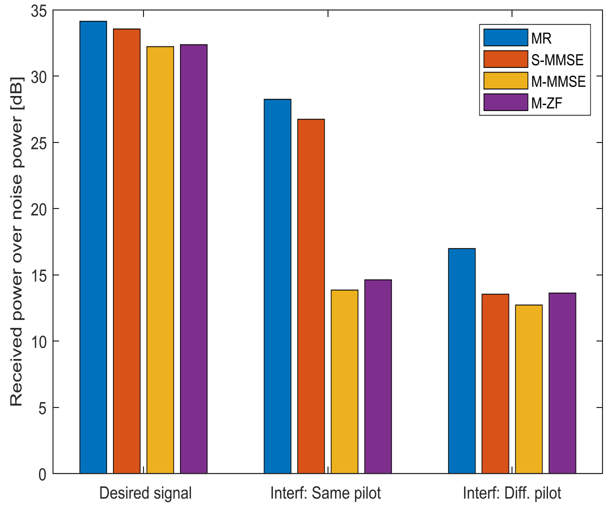

Fig.7. UL received signal power after combining

When the SNR in the DL is equal to the SNR in the UL and provide sub optimal solution to achieve unbounded SE in the UL. In order to get sub-optimal solution, the average fading and spatial channel correlation were considered. It is noted that the higher SE is achieved with increasing SNR. Here, the SE of the massive MIMO system is function of SNR. The SNR is increased by deploying massive BS antennas that is $M \rightarrow \infty$. But it only theoretical assumption to achieve the un -bounded SE. The sub-optimal solution is implemented in Fig.5 by using EW-MMSE. This demonstrates the SE with full channel covariance matrices.

Table- II: Received power levels over noise

S.No	**Comparison of received power levels**		
	Scheme	***Proposed received power (dB)***	***received power (dB)***
1	MRC	34	24 [22]
1	S-MMSE	33	23.8 [22]
1	M-MMSE	32	23 [22]
1	M-ZF	33.2	22 [22]

V. CONCLUSION

In this paper, we demonstrated the achievable capacity of Massive MIMO systems in the presence of PC. It is observed that the asymptotic capacity obtained when the BS antennas tends to infinity. The throughput increases without bound by using MMSE combining/precoding.

We analyzed the SE with linear processing schemes M-MMSE, S-MMSE, M-ZF, and MRC. The impact of spatial correlation factor on the SE was exploited with covariance matrices. These matrices were assumed as spatially independent and designed to achieve maximal throughput. The maximum SE of 4.5 bits/s/Hz was achieved with MMSE scheme when using same pilot. The low SE of 2 bits/s/Hz was identified with MR scheme. It is noticed that the maximum received signal power of 34 dB provided by the MRC while M-MMSE scheme was observed with low value of 32dB. Both M-MMSE and M-ZF schemes outperform than the S-MMSE and MRC by comparing SEs and desired signal power over noise.

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