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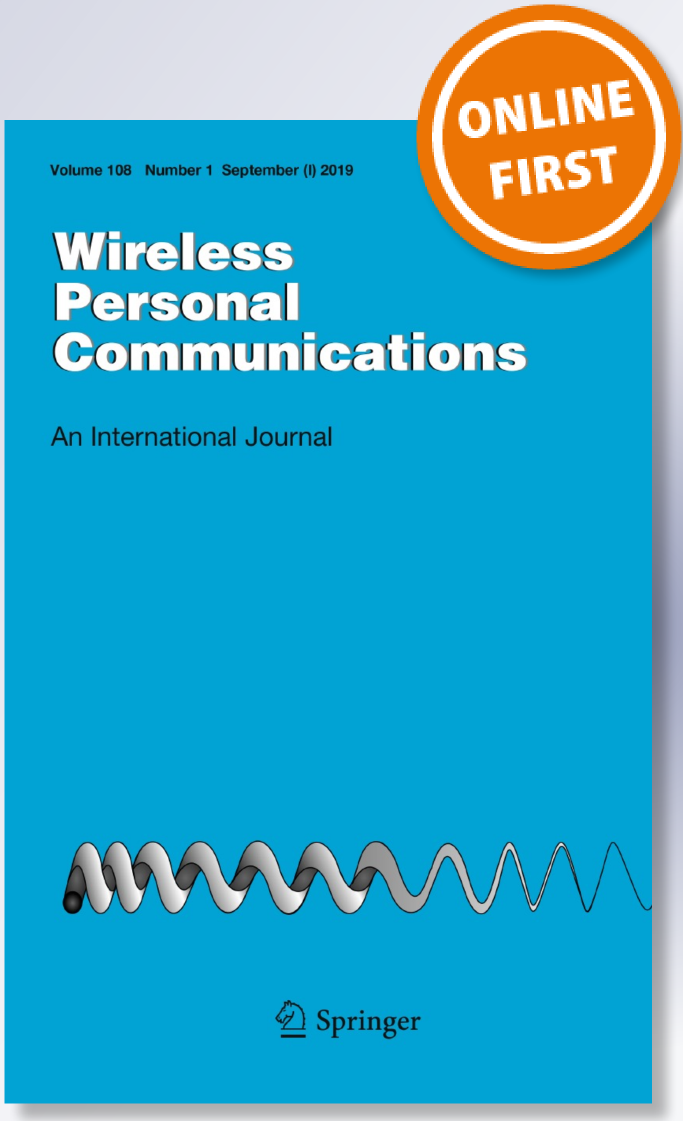

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Linear Precoding with User and Transmit Antenna Selection

Ashu Taneja[1] · Nitin Saluja[2]

Abstract
The major challenge in the current scenario of wireless system is increasing number of users and hence increased co-channel interference within the limited spectrum available for communication. The compromise in terms of user quality and reliability of communication system is evitable from increased number of call drops and busy channels during mobile voice calls. The above mentioned challenge is attributed for increase in the number of users accommodated in the defined spectrum. The paper presents a novel user selection and transmit antenna selection based approach for enhanced reliability in multi-user multiple input multiple output system, which is next generation wireless system. In contrast to existing technique for multiple antennas and which is evolution of regular channel inversion with block diagonalization, the proposed technique considers systematic and optimum deployment of user selection in the system to enhance sum rate or the system capacity. The comparison of algorithms viz. random, norm based and capacity based user selection is presented with its implementation with precoding techniques which is used to minimize co-channel interference. The analysis proposes that, for each selected user if the transmit antennas are chosen with presented algorithm, the sum rate is improved by 17%. Also, the bit error rate performance of linear precoding with user selection is equivalent to non-linear precoding without user selection.

Keywords MIMO · MU-MIMO · ZF · MMSE · BD · BS · BER · SNR

1 Introduction

The performance of next generation wireless communication in terms of user capacity and communication reliability is enhanced using multiple antenna systems [1–5]. As the number of users have increased exponentially in past few years and after the successful commercialization of MIMO system, the focus has been shifted to multi-user MIMO (MU-MIMO) systems. MU-MIMO system serves numerous users in the same time–frequency

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interval using multiple antennas deployed at the base station (BS) [6–8]. In general, MU-MIMO systems suffer from the main challenge of inter-user interference and it significantly reduces the system performance. However, in specific case of downlink MU-MIMO, the interference is mitigated using several precoding techniques explained in literature [9–19]. These precoding techniques exploit the transmit diversity by weighting information stream by a factor depending on channel condition. It reduces the error incurred during transmission. The enhanced performance using precoding techniques are limited by a compromise between computational complexity and reduction in bit error rate as in case of Dirty-paper coding (DPC) that achieves the optimal capacity [9] but it is still not popular in existing systems due to its high computational complexity. The high computational complexity in DPC is attributed to non-linearity in it. Another non-linear precoding proposed in literature is Tomlinson–Harashima precoding [10] which uses modular operation at both transmitter and receiver which is also impractical in real-time implementation with current capacity of processors. In existing scenario, the linear precoding technique is preferred due to its practicality being less complex. Hence the paper considers linear precoding technique in the system implementation. In literature, authors have analyzed the performance of linear precoding in different fading environments, as the channel inversion and regularized channel inversion for MU-MIMO system with a simple Rayleigh fading model being analyzed in [11] while [12, 13] analyzes MU-MIMO system with zero forcing (ZF) precoding and regularized ZF precoding in Ricean fading environment. It is concluded that large scale antenna array systems (LSAS) use Ricean fading model involving dominant line-of-sight component which can be avoided otherwise, so it is generalized to study Rayleigh fading model and hence considered in the system presented in paper. Further, the generalization of channel inversion is Block-Diagonalization [14] which highlights that the precoding matrix for one user should lie in the null space of other users' channels. It also claims that the number of users in block diagonalization is constrained by the number of antennas at each user terminal. The proof of concept for validation of performance evaluation provided in theories applicable to different precoding techniques in different parametric conditions are given in [15]. Additionally, the number of such precoding techniques based on block diagonalization are defined in literature viz. the multi-user eigen-mode transmission being disclosed in [16, 17]. It is concluded from above discussion that the block diagonalization is more practical approach and commonly used in today's wireless communication system than counterpart non-linear precoding techniques but it constraint the number of users or capacity of the system. It encouraged the research in the area of improvement in the process of block diagonalization for reduction in complexity of pre-coding technique which allows efficient utilization of pre-coding. Similarly, the MU-MIMO system as defined above is characterized by more than one antenna for each user and base station, the user selection algorithm is proposed in literature for optimizing number of users [18]. It is considered to have same number of antennas at each user with BD precoding and still offer increased user capacity. The paper in [19] compares BD with Zero-forcing combining (ZFC) for MU-MIMO system and also analyzes the impact of user selection on system performance. Very few papers have considered the impact of antenna selection for each scheduled user on the performance of MU-MIMO system. [20] considers transmit antenna selection for MIMO systems with spatial modulation schemes while [21] talks about transmit antenna selection with BD for downlink MU-MIMO but both does not take into account user selection.

This paper provides a novel technique for a MU-MIMO system which is a combination of precoding, user selection and transmit antenna selection for each scheduled user. The common precoding techniques considered are ZF and MMSE for users with single antenna and BD for users with multiple antennas. The sum rate is evaluated and it is seen how number of BS antennas (N_T), number of users (K), number of antennas per user (M) and the ratio K/M affect the sum rate. Then, the impact of user selection on the performance is seen using three different user scheduling techniques namely random user selection, norm-based user selection and capacity-based user selection. After that, for each scheduled user, a subset of transmit antennas is selected using norm-based antenna selection. The effect of varying the total number of users on the sum rate considering both user selection and antenna selection is also presented. In the end, the BER performance analysis is carried out for non-linear and linear precoding with and without user selection.

The novel contributions of the paper are summarized as:

- It is shown that for a MU-MIMO scenario with fixed number of BS antennas and the growing number of users, linear precoding can outperform or perform equivalent to non-linear precoding (used to mitigate interuser interference) when the optimized user selection algorithm is considered. It requires system parameters like capacity or channel information as an input parameter to capacity based and norm based user selection algorithms. High sum rate can be obtained with capacity based and norm based user selection compared to random user selection.
- The MU-MIMO analysis is presented with parametric variations in number of BS antennas (N_T), number of users (K), number of antennas per user (M) and the ratio K/M and for proposed algorithm the data is required for optimization of these parameters.
- An antenna selection scheme complementing the proposed user selection algorithm and scheduling users using Frobenius norm of the channel is proposed. Hence the complete system which increases the sum-rate without contributing to the complexity of the MU-MIMO systems. It is shown that sum rate is increased by incorporating both user selection and antenna selection algorithms.

The remainder of this paper is organized as follows: Sect. 2 introduces the system model. Precoding techniques for MU-MIMO is presented in Sect. 3. User scheduling algorithms are described in Sect. 4. Section 5 gives details of transmit antenna selection algorithm. The simulation results are shown in Sect. 6. Section 7 gives the conclusion.

2 System Model

Consider a downlink MU-MIMO system with K users and each user with M number of antennas as shown in Fig. 1. Users communicate through a BS having total of N_T number of antennas. The received signal at the kth user is given by

$$y_k = H_k x + n_k \quad where\ k = 1, 2 \ldots K \tag{1}$$

where $x \in \mathbb{C}^{N_T \times 1}$ and is the transmitted signal vector, $H_k \in \mathbb{C}^{M \times N_T}$ is the channel matrix of the kth user and $n_k \in \mathbb{C}N(0, 1)$ is the complex additive white guassian noise at the kth user.

It is assumed that $H_1, H_2, \ldots H_K$ are known at the transmitter and the transmitter is subject to an average power constraint, i.e. $E\{x^H x\} \le P$. Also, large spacing between transmitter antenna elements and the user terminals is assumed and hence the spatial correlation is negligible both at the transmitter and the receiver. A Rayleigh small scale fading environment is assumed for transmission. The element of the channel matrix is given in a complex number form as [22]

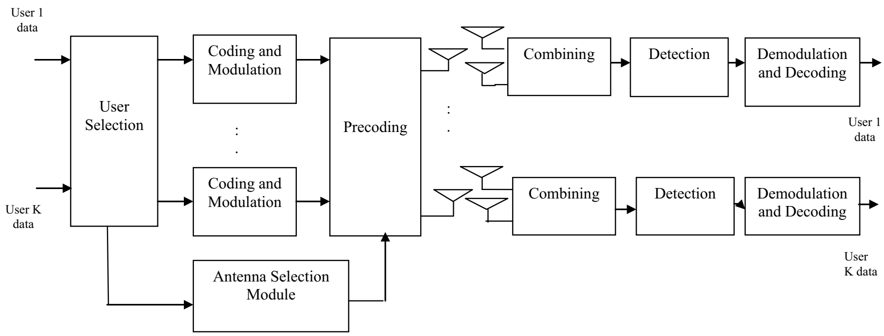

Fig. 1 Block diagram of MU-MIMO system with user selection, antenna selection for scheduled users and precoding

$$h_{ij} = a + jb \tag{2}$$

The joint probability density function (PDF) is given by

$$f_{ab}(a, b) = 1$$

$$f_{ab}(a, b) = \frac{1}{2\pi\sigma^2} \exp\left(-\frac{a^2 + b^2}{2\sigma^2}\right) \tag{3}$$

where a and b are the two Gaussian random variables with zero mean and variance 0.5 [23].

3 Precoding Techniques

The paper considers the comparison of three linear precoding techinques which are compared for performance in MU-MIMO systems. Precoding is a technique in which interference due to signals to other users is eliminated by multiplying the user data with the precoding matrix before transmission [24]. Figure 2 shows the system model for precoding. Let W $\in C^{M\times K}$ be a linear precoding matrix and s is the precoded symbol vector given as

$$s = Wx \tag{4}$$

where x is the original symbol vector for transmission.

Then, the received signal vector is written as

$$y = \frac{1}{\beta}(Hs + z) \tag{5}$$

$$y = \frac{1}{\beta}(HWx + z) \tag{6}$$

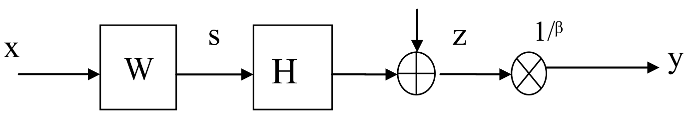

Fig. 2 System model for precoding [25]

where β is the amplification factor at the transmitter. For a MU-MIMO system with K single antenna terminals and N_T antennas at the base station, precoding techniques like channel inversion and regularized channel inversion are used for which $N_T \geq K$ is assumed. On the other hand, for multiple-antenna users, block-diagonalization approach is considered to eliminate the interuser interference which assumes $N_T \geq M \times K$.

3.1 Channel Inversion (Zero Forcing Precoding)

It is a linear pre-coding technique in which the effect of inter-user interference is cancelled out at each user [26, 27]. Let W_k be the precoding vector of the kth user. The precoder design forces zero interference as follows

$$H_k W_j = 0 \; for \; j \neq k \tag{7}$$

The precoding matrix is chosen as

$$W_{ZF} = H^H \left(HH^H\right)^{-1} \tag{8}$$

Hence, the achievable sum rate from used precoding technique is given as

$$R_{ZF} = \sum_{k=1}^{K} log_2\left(1 + \frac{P}{K\sigma^2}\left|H_k W_k\right|^2\right) \tag{9}$$

3.2 Regularized Channel Inversion (MMSE Precoding)

Another linear precoding technique is the regularized channel inversion also called Minimum mean square error (MMSE) precoding which is given as [28]

$$W_{MMSE} = H^H \left(HH^H + \frac{\sigma_z^2}{\sigma_x^2} I \right)^{-1} \tag{10}$$

The achievable sum rate is given as

$$R_{MMSE} = \sum_{k=1}^{K} log_2\left(1 + \frac{\left|H_k w_k\right|^2}{\sum_{j\neq k}\left|H_k w_j\right|^2 + K\sigma^2/P} \right) \tag{11}$$

3.3 Block-Diagonalization Precoding

The aim is to design an optimal precoding vector W such that multi-user interference is zero. This is possible when W_j lies in the null space of H_k^* which is defined as

$$H_k^* = [H_1^T \dots H_{k-1}^T H_{k+1}^T \dots H_K^T]^T \tag{12}$$

The singular value decomposition of H_k^* is given as [29]

$$H_k^* = U_k^* S_k^* \left[V_k^{*(1)} V_k^{*(0)} \right]^H \tag{13}$$

where U_k^* is the left singular vector matrix, S_k^* is the matrix of singular values of H_k^*. $V_k^{*(1)}$ and $V_k^{*(0)}$ are the right singular matrices corresponding to non-zero singular values and zero singular values. Any precoder W_k that is linear combination of columns of $V_k^{*(0)}$ will satisfy the null constraint and will produce zero interference at other users.

$$H_k V_k^{*(0)} = U_k \begin{bmatrix} S_k & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_k^{(1)} & V_k^{(0)} \end{bmatrix}^* \tag{14}$$

The achievable sum rate is given by

$$R_{BD} = \sum_{k=1}^{K} log_2\left(I + \frac{P}{K} H_k W_k W_k^H H_k^H\right) \tag{15}$$

4 User Selection

In general, there are numerous users in a wireless system. But the number of transmit antennas at the BS can support a few users at a time. To select a suitable subset of users from the pool of available users is the main purpose of user selection algorithms [30–34]. The paper considers the comparison of three user scheduling algorithms which are compared for performance in MU-MIMO systems. Let K_T denotes the total number of users in the system, out of which K users are selected using user scheduling algorithms.

4.1 Random User Selection

In this scheme, a subset of K users are selected from K_T users by the base station randomly. Here it is assumed that the channels state information is identically distributed for all users.

4.2 Norm Based User Selection

The total power gain of the user's channel is its squared Frobenius norm. In this scheme, each user calculates the squared Frobenius norm of its channel matrix, H_k and sends this value to the base station [35].

$$||H||_F^2 = trace\left(H_k H_k^H\right) \tag{16}$$

The BS receives K_T norm values, one from each user. It sorts these values and selects the user with the maximum norm value. It repeats this process until all K users are selected.

Norm Based User Selection Algorithm

1. Suppose $\Omega = \{1,2 \ldots K_T\}$ defines a set of all users and $\lambda = \{\varphi\}$ is the set of selected users.
2. Find $\left|\left|H_k\right|\right|_F^2$ for $\in \Omega$.
3. Let $s = \arg max \left|\left|H_k\right|\right|_F^2$ where $k \in \Omega$.
4. $\Omega = \Omega - \{k\}$ and $\lambda = \lambda + \{k\}$.
5. Repeat the process from step 2 till K users are selected.

4.3 Capacity Based User Selection

This scheme first of all finds the user with the highest capacity. Then, from the unselected users, it finds the user that gives highest throughput together with those selected users. This process continues till K number of users get selected.

$$C_k = log_2\left(I + \frac{1}{\sigma^2}H_k W_k W_k^H H_k^H\right) \tag{17}$$

Capacity-Based User Selection Algorithm

1. Suppose $\Omega = \{1,2\ldots K_T\}$ defines a set of all users and $\lambda = \{\varphi\}$ is the set of selected users.
2. Find $C_k = log_2\left(I + \frac{1}{\sigma^2}H_k W_k W_k^H H_k^H\right)$ for $k \in \Omega$.
3. Let $s = \arg\max C_k$ where $k \in \Omega$.
4. $\Omega = \Omega - \{k\}$ and $\lambda = \lambda + \{k\}$.
5. Repeat the process till K users are selected.

5 Antenna Selection

The antenna selection is performed after the user selection explained in the later section. It is considered that a subset λ of K users is selected followed by the selection of transmit antennas [36–40]. Consider that a subset of transmit antennas is T_k where $k \in \lambda$. In the transmit antenna selection algorithm, at each stage, a particular user is considered viz. user k. The receive antennas for user k (M in this case) are considered as the transmit antennas and the antennas at the base station not yet allocated are considered to be the users (each with a single antenna). The channel is assumed as reciprocal and norm-based antenna selection algorithm is used to choose a set of M antennas corresponding to the strongest orthogonal channels from the user to the BS. User k selects its subset of transmit antennas T_k from the available antennas. The information regarding the indices of selected antennas is then sent to the BS. Finally, the BS updates the set of available transmit antennas to the next user in order. In this way, the selected users are assigned the set of transmit antennas.

Norm Based Antenna Selection Algorithm

1. Suppose $\Omega = \{1,2\ldots N_T\}$ defines a set of all transmit antennas and $T_k = \{\varphi\}$ is the set of selected transmit antennas for user k.
2. Find $\left\|h_j\right\|_F^2$ where $j \in \Omega$.
3. Find $\gamma_i = argmax_j\left\|h_j\right\|_F^2$.
4. Update $\Omega = \Omega - \{j\}$ and $T_k = T_k + \{j\}$.
5. Repeat till T_k contains M elements.
6. Continue the process for all K users.

6 Simulation Results

In this section, the performance of MU-MIMO downlink system is compared for different precoding, user selection and transmit antenna selection models. The first block in the system model is precoding technique and hence in Fig. 3, the comparison of the channel

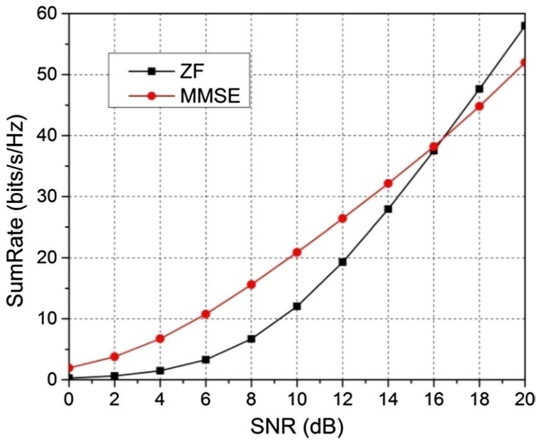

Fig. 3 Comparison of ZF and MMSE Precoding for MU-MIMO system with $N_T = 8$, $K = 8$ and $M = 1$

inversion (ZF) and regularized channel inversion (MMSE) is presented for proposed system. It is considered that the BS has $N_T = 8$ and the number of users $K = 8$ each with single antenna $M = 1$. It is analyzed that the MMSE outperforms ZF precoding in low SNR ranges but at high SNR, ZF outperforms MMSE. The analysis presents essential decision criteria for optimized precoding technique in MU-MIMO systems in specified conditions.

The analysis is followed by parametric analysis for used precoding technique. In Figs. 4 and 5, the block-diagonalization precoding is compared for different values of number of transmitter antennas N_T where $M = 2$ and varying system under proposed system conditions. It is analyzed that, the sum rate increases by around 44% as N_T is increased from 50 to 100 at SNR of 16 dB and the sum-rate difference increases with increasing values of SNR. The increase in the sum-rate difference is attributed to signal power as at low SNR the signal is less and hence the effect of interference is less as compared to the effect at high SNR which is rather mitigated by the precoding schemes thereby increasing the sum rate.

Figure 5 illustrates that for a fixed N_T, as the ratio K/M is increased, the sum rate decreases. It can also be seen in Table 1 for different N_T. While it is important to infer that, as the number of antennas per user are increased with fixed N_T, the sum rate increases. It

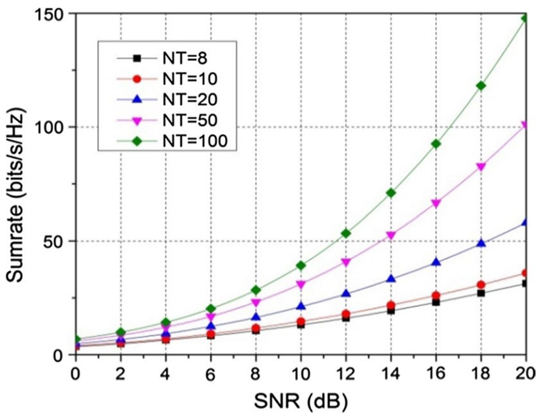

Fig. 4 Block-diagonalization precoding for varying N_T with $M = 2$ and $K = N_T/M$

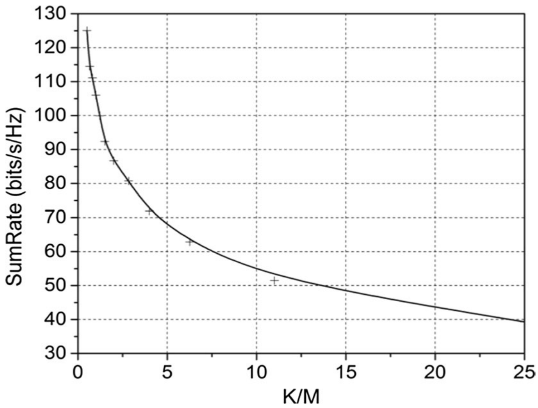

Fig. 5 Sum rate versus K/M for a fixed $N_T = 100$

Table 1 Values of sum rate for different N_T, K and M

N_T	K/M	Sum rate at SNR = 10 dB (bits/s/Hz)	N_T	K/M	Sum rate at SNR = 10 dB (bits/s/Hz)
8	0.5	14.62	100	0.5	125.0102
	2	10.55		0.66	114.4675
10	0.4	18.24		0.81	111.1067
	2.5	14.63		1	105.998
20	0.8	33.3745		1.22	99.9342
	1.25	30.0877		1.5	92.3475
	5	21.1680		2	86.6456
50	0.5	75.1451		2.83	80.6869
	0.75	65.9196		4	71.9287
	1	62.7465		6.25	62.8216
	1.33	57.2706		11	51.4849
	2	53.2072		25	39.3018
	3.25	47.5692			
	5.66	39.3382			
	12.5	31.1415			

is another essential analysis to optimize parameters like N_T, K and M for specified SNR range.

After defining the optimized system parameters including the suitable precoding technique and the parameters for specified values of SNR, the effect of user selection is analyzed. In Fig. 6, the effect of user selection algorithm in MU-MIMO system is depicted. The capacity-based user selection algorithm is considered and offers the increase in 17–29% increase in sum-rate for SNR range of 0 to 20 dB.

Further, three different types of user selection algorithms are compared in Fig. 7 for block diagonalization precoding while $N_T = 8$, $K = 4$ and $M = 2$ in MU-MIMO system. It concludes that the capacity based user selection outperforms norm-based user selection and random user selection by 19% and 25% respectively at SNR of 16 dB. Further the user selection block is followed by antenna selection algorithm and hence the comparison

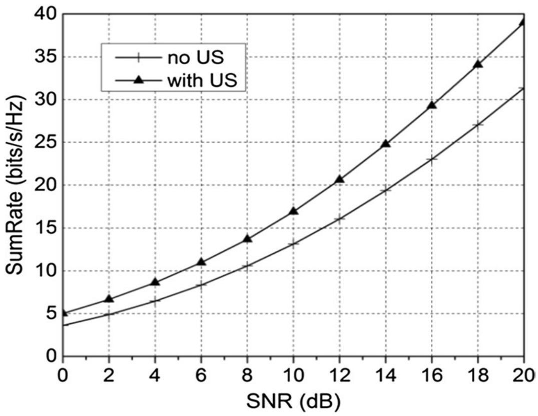

Fig. 6 Sum rate versus SNR for a MU-MIMO system ($N_T=8$, $K=4$ and $M=2$) with user selection and without user selection

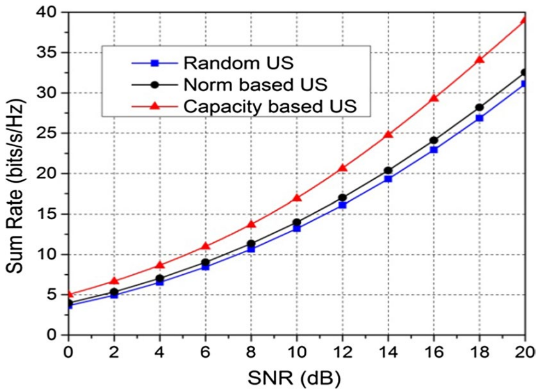

Fig. 7 Comparison of different user-selection algorithms with BD precoding for downlink MU-MIMO with $N_T=8$, $K=4$ and $M=2$

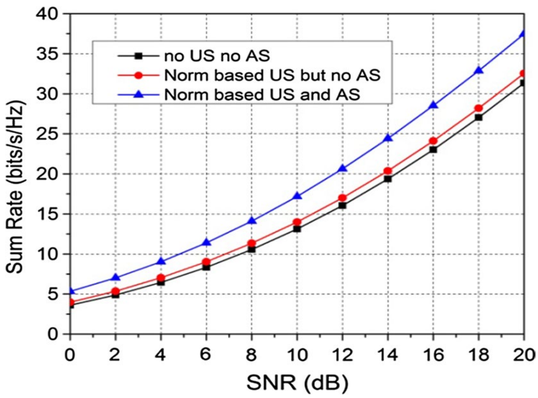

Fig. 8 Sum rate versus SNR on applying norm-based antenna selection

of norm-based antenna selection is analyzed to select a subset of antennas at the BS for each scheduled user. The sum rate further improves by 17% which is analyzed in Fig. 8. In Fig. 9, the bar graph clearly indicates the improvement of proposed MU-MIMO system with norm based US and norm based AS over existing US based systems. It is inferred that the proposed system can offer significant improvement and hence increased spectral

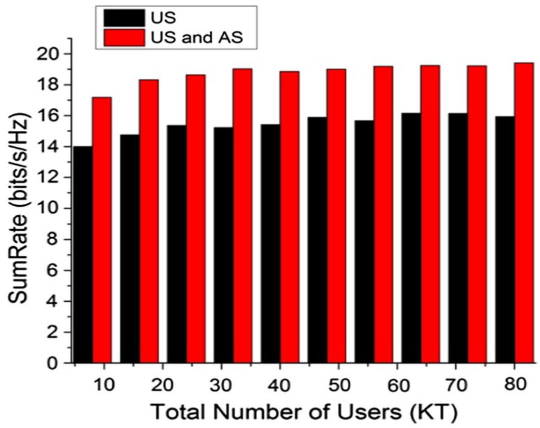

Fig. 9 Sum rate versus total number of users with both user selection and antenna selection

efficiency. Further it is essential to validate the concept for increased number of users and the results are non-variable with increase in number of users and limits depends upon performance of different radio frequency front end components. The proposed system is significantly less complex (almost 40% reduced computations) than non-linear precoding and even offers almost equal performance in terms of spectral efficiency and also verified in Fig. 10. It rather proves the usability of proposed system in real time communication systems with enhanced spectral efficiency.

7 Conclusion

In this paper, channel-inversion and regularized channel inversion precoding is applied to a downlink MU-MIMO system with single antenna users to compensate for co-channel interference while block-diagonalization precoding is considered for users with multiple antennas to see that as the number of antennas at the BS is increased, the sum rate is increased. Also, for a fixed N_T, as the ratio K/M increases, the sum rate decreases. It is seen that on applying user scheduling to choose a set of users, the sum rate further improves by 17–29%. Comparison of different user-scheduling algorithms suggests that capacity-based user selection algorithm outperforms both norm-based user selection and random user

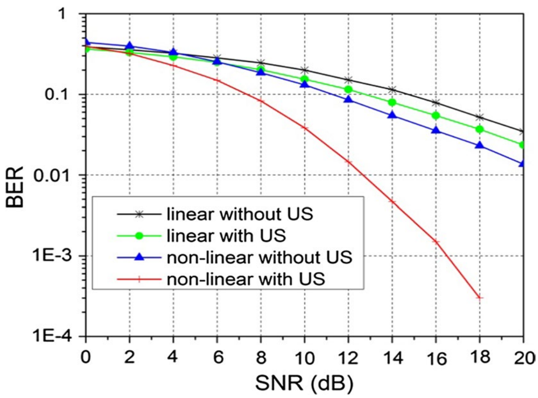

Fig. 10 BER performance of linear and non-linear precoding with and without user selection

selection by increasing the sum rate by 19% and 25% respectively. Then, for the selected users, a subset of transmit antennas at the BS are selected using norm-based antenna selection to see that the sum rate get enhanced by 17%. It is concluded that the proposed system offers superior/equal sum-rate performance to non-linear precoding with reduced complexity up-to 40%. The system is non-variant with increased number of users proving its applicability in scaled version of the communication systems. The proposed system can easily be implemented in real time wireless communication systems.

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