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Performance Analysis of Different Transmission Methods for Broadcast Channels in MU-MIMO

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Abstract: ***Multi-user MIMO system is affected by Multiple Access Interference (MAI) caused by the simultaneous transmission of multiple users which limits capacity and performance of CDMA system. Since the data recovery at the receiver side is not straight-forward, these interferences cause error bit while reconstructing the signal. So, different transmission methods are adopted to cancel out these interferences where the signals are precoded before transmission. Channel inversion, Dirty paper coding and Tomlinson Harashima Precoding are some of these methods which cancel outs the effects of Inter-symbol interference by means of Channel state information feedback. This paper discusses about these transmission methods for broadcast channels in multi-user MIMO. First we discuss the mathematical model of Multi-user MIMO system. Then we analyse the performance of different transmission methods for broadcast channels in terms of bit error rate (BER). Finally, we make a comparison among these methods by their performance.***

Keywords: Multi user MIMO, Channel inversion, Dirty Paper coding, Tomlinson Harashima Precoding, Bit Error Rate (BER), Inter-symbol Interference (ISI), Decision Feedback Equalization (DFE)

1. Introduction

In MIMO system independent users are allowed to transmit their own data stream into uplink (many-to-one) at the same time or base station is allowed to transmit the multiple user data streams to be decoded by each user in downlink (one-to-many). In multi user MIMO the main problem is inter-channel interference and fading. These change the received signal from transmitted signal and as a result error bits are present in the reconstructed data. These interferences can be minimized by precoding data before transmitting. Different transmission methods like channel inversion, Dirty paper coding, Tomlinson Harashima precoding are adopted which cancel outs the interferences by means of Channel state information. Channel state information is estimated in the receiver side and fed back to the transmitter side. [1][7]

Channel inversion is the same process as zero forcing pre-equalization. It nullifies the interferences by multiplying a weight matrix consists of channel matrix and its Hermitian transpose operation.

Dirty paper coding (DPC) is a method of precoding the data by subtracting the potential interferences such that the effect of the interference can be canceled out. This method can be implemented when the channel gain is completely known to the transmitter side by feedback. DPC on the transmitter side is very similar to the Decision Feedback Equalization (DFE).

Tomlinson-Harashima Precoding is equivalent to the combination of DPC with symmetric modulo operation. Tomlinson-Harashima precoding is a method that cancel the post cursor Inter-Symbol Interference(ISI) in the transmitter, where the past symbols are completely known without possibility of error. A complete knowledge of channel impulse response is required, available by the CSI feedback system for time invariant or slowly time variant channel. [1]

In the first section we will discuss about the mathematical model of multi-user MIMO.

Then we will show the analytical discussion of the three transmission methods for downlink in multi-user MIMO. We will analyse the performance of the transmission methods in terms of Bit Error Rate (BER) and make a comparison among their performance.

2. Multi User MIMO

Multi user MIMO is a system where a numbers of users are present, some of them are active and some are inactive sharing the same radio resources. The figure below describes the environment of a multi user MIMO system served by a single base station in a cellular system.

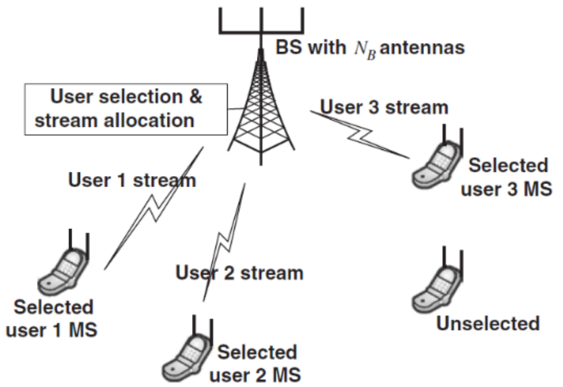

Figure 1: Multi User MIMO system [1]

The uplink channel is known as the multiple access channel (MAC) and the down link known as broadcast channel.
The received signal is expressed as [2, p-396].,

$$y_{mac} = H_1^{UL} x_1 + H_2^{UL} x_2 + \dots + H_k^{UL} x_k + Z$$

$$= \begin{bmatrix} H_1^{UL} & H_2^{UL} & \dots & H_k^{UL} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \cdot \\ x_k \end{bmatrix} + Z$$

$$= H^{UL}\begin{bmatrix} x_1 \\ x_2 \\ . \\ x_k \end{bmatrix} + Z \quad (1)$$

Here, $x_u \in C^{N_B \times 1}$ is the transmit signal from u[th] user
$y_{MAC} \in C^{N_B \times 1}$ is the received signal at the BS
$H_u^{UL} \in C^{N_B \times N_M}$ is channel gain between the u[th] user and BS
$C^{N_B \times N_M}$ is the orthogonal space time block code matrix
Similarly, for downlink signal at the u[th] user,

$$y_u = H_u^{DL} + Z_u \quad (2)$$

Here, $Z_u \in C^{N_B \times 1}$ is the additive noise
$H_u^{DL} \in C^{N_B \times N_M}$ is channel gain between the BS and u[th] user
Considering all the users the total signal is [1, p-397].,

$$\begin{bmatrix} y_1 \\ . \\ . \\ y_k \end{bmatrix} = \begin{bmatrix} H_1^{DL} \\ . \\ . \\ H_k^{DL} \end{bmatrix} x + \begin{bmatrix} z_1 \\ . \\ . \\ z_k \end{bmatrix} \quad (3)$$

3. Different methods of Transmission for Broadcast Channels

As the coordinated signal detection on the receiver side is not straight-forwarded, to cancel out interferences different precoding transmission methods are adopted. In this section we will discuss some of them.

3.1 Channel Inversion

Let us consider a system where total number of active user is k, number of receive antenna at mobile user N_M =1, number of base station antenna N_B =k. The received signal of u[th] user is,

$$y_u = H_U^{DL}\begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \\ . \\ \tilde{x}_k \end{bmatrix} + z_u ; u = 1,2....k \quad (4)$$

Here $H_u^{DL} \in C^{1x3}$ is channel matrix between BS and u[th] user. Channel inversion nullifies the interference by the following weight matrix multiplied with the transmitted symbols [3],

$$W = \left(H^{DL^H} H^{DL} \right)^{-1} H^{DL^H} \quad (5)$$

The transmitted signal is precoded as,

$$x_u = W.\tilde{x}_u$$

Here x is the pre-coded symbol and $\tilde{x}_u$ is the original orthogonal symbol for transmission. Channel inversion method provides the received signal as,

$$y = \frac{1}{\beta}(H.\beta.x_u + z)$$

$$= \frac{1}{\beta}\left\{ \left(H^{DL^H} H^{DL} \right)^{-1} H^{DL^H} .\beta.H^{DL^H} H^{DL}.\tilde{x}_u + z \right\}$$

$$y = \tilde{x} + \frac{1}{\beta} z \quad (6)$$

Where, $\beta = \sqrt{\frac{N_T}{T_r\left(W.W^H\right)}}$ is a constant to meet the total transmitted power constraint after pre-equalization.

This received signal is sent to the maximum likelihood detector. Noise enhancement can be mitigated using MMSE criterion. The weight matrix of MMSE is given as,

$$W = \left(H^{DL^H} H^{DL} + \frac{\sigma_z^2}{\sigma_x^2} I \right)^{-1} H^{DL^H} \quad (7)$$

In the context of multi-user MIMO, using this weight matrix of MMSE instead of equation (7) is called regularized channel inversion.

Interference due to other signals can be cancelled out by channel inversion and regularized channel inversion where each user is equipped with single antenna. [4][5][6]

3.2 Dirty Paper Coding

By subtracting the potential interferences before transmission an interference-free transmission can be realized. Dirty Paper Coding schemes use the channel state information (CSI), available at the transmitter by means of feedback, and the a priori known users' data to eliminate or reduce the interference.

Let us consider a case with number of transmit or base station antenna NB =3, k=3, $N_{M,u}$ =1. If the u-th user signal is denoted by $\tilde{x}_u \in C$ and the received signal [1,p-409][7],

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \begin{bmatrix} H_1^{DL} \\ H_2^{DL} \\ H_3^{DL} \end{bmatrix} \begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \\ \tilde{x}_3 \end{bmatrix} + \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} ; H_u^{DL} \in C^{1x3}$$

Channel matrix can be decomposed as LQ [1],

$$H^{DL} = \begin{bmatrix} l_{11} & 0 & 0 \\ l_{21} & l_{22} & 0 \\ l_{31} & l_{32} & l_{33} \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix}$$

Let, $x = [x_1 \quad x_2 \quad x_3]$ is pre-coded signal for $\tilde{x} = [\tilde{x}_1 \quad \tilde{x}_2 \quad \tilde{x}_3]^T$ then the received signal is given as [1,p-409],

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \begin{bmatrix} H_1^{DL} \\ H_2^{DL} \\ H_3^{DL} \end{bmatrix} Q^H x + \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} = \begin{bmatrix} l_{11} & 0 & 0 \\ l_{21} & l_{22} & 0 \\ l_{31} & l_{32} & l_{33} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} \quad (8)$$

The first user signal can be written as [1, p-409],

$$y_1 = l_{11}x_1 + z_1 \quad (9)$$

$$x_1 = \tilde{x}_1 \quad (10)$$

The second user signal can be written as [1, p-410],

$$y_2 = l_{21}x_1 + l_{22}x_2 + z_2 \quad (11)$$

$$x_2 = \tilde{x}_2 - \frac{l_{21}}{l_{22}} x_1 \quad (12)$$

The third user signal can be written as [1, p-410],

$$y_3 = l_{31}x_1 + l_{32}x_2 + l_{33}x_3 + z_3 \quad (13)$$

$$x_3 = \tilde{x}_3 - \frac{l_{31}}{l33} x_1 - \frac{l_{32}}{l_{33}} x_2 \quad (14)$$

We can write the precoded signals as a matrix by using eq (10), (12), (14) as,

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ -\frac{l_{21}}{l_{22}} & 1 & 0 \\ -\frac{l_{31}}{l_{33}} + \frac{l_{32} l_{21}}{l_{33} l2} & -\frac{l_{32}}{l_{33}} & 1 \end{bmatrix} \begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \\ \tilde{x}_3 \end{bmatrix} \quad (15)$$

Using eq. (15) we can re-write eq. (8) as,

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \begin{bmatrix} l_{11} & 0 & 0 \\ l_{21} & l_{22} & 0 \\ l_{31} & l_{32} & l_{33} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ -\frac{l_{21}}{l_{22}} & 1 & 0 \\ -\frac{l_{31}}{l_{33}} + \frac{l_{32} l_{21}}{l_{33} l2} & -\frac{l_{32}}{l_{33}} & 1 \end{bmatrix} \begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \\ \tilde{x}_3 \end{bmatrix} + \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix}$$

$$= \begin{bmatrix} l_{11} & 0 & 0 \\ 0 & l_{22} & 0 \\ 0 & 0 & l_{33} \end{bmatrix} \begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \\ \tilde{x}_3 \end{bmatrix} + \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} \quad (16)$$

Users are selected such that [3, p-412],

$$l_{u_1^* u_1^*} \geq l_{u_2^* u_2^*} \geq l_{u_3^* u_3^*} \geq l_{uu}$$

Where $\left(u_1^*, u_2^*, u_3^*\right) \in \{1,2,3 \ldots k\}$ are user indices. Selection of the users with the largest l_{ii} ensures to minimize the noise enhancement on the receiver side.

3.3 Tomlinson Harashima Precoding

Tomlinson-Harashima (TH) precoding is the combination of Dirty Paper Coding and modulo operation. Decision-feedback equalization (DEF) is a non-linear equalization approach at the receiver side. The original idea of TH precoding in DFE is to Cancel the post-cursor ISI in the transmitter, where the past transmit symbols are known without possibility of errors. [8][9][10]

An expanded symbol c is obtained by adding 2A.m to the data symbol x, where A is an even integer, $A = \sqrt{M}$ and data symbol x is drawn from the M-ary PAM constellation. [1, p-412] [9]

$$c = x + 2A.m$$

To reduce the peak or average power, m must be chosen to minimize the magnitude of c. The original data symbol x can be recovered from c by the symmetric modulo operation defined as,

$$x = \text{mod}_A(c) \overset{\Delta}{=} c - 2A\left\lfloor \frac{c+A}{2A} \right\rfloor$$

The symmetric modulo operation is defined as,

$$\text{mod}_A(x) = x - 2A\left\lfloor \frac{x + A + jA}{2A} \right\rfloor \quad (17)$$

By finding the value of integer m, n we can write the modulo operation as,

$$\text{mod}_A(x) = x + 2A.m + j2A.n \quad (18)$$

Let a system with k=3, $\left\{x_u^{TH}\right\}_{u=1}^{3}$ denote the TH precoded signal for the u th user. The data symbols are represented as,

$$x_1^{TH} = \text{mod}_A(\tilde{x}_1) \quad (19)$$

$$x_2^{TH} = \text{mod}_A\left(\tilde{x}_2 - \frac{l_{21}}{l_{22}} x_1^{TH}\right)$$

$$= \tilde{x}_2 - \frac{l_{21}}{l_{22}} x_1^{TH} + 2A.m_2 + j2A.n_2 \quad (20)$$

$$x_3^{TH} = \text{mod}_A\left(\tilde{x}_3 - \frac{l_{31}}{l_{33}} x_1^{TH} - \frac{l_{32}}{l_{33}} x_2^{TH}\right)$$

$$= \tilde{x}_3 - \frac{l_{31}}{l_{33}} x_1^{TH} - \frac{l_{32}}{l_{33}} x_2^{TH} + 2A.m_3 + j2A.n_3 \quad (21)$$

For the transmitted signal $Q^{H..}x^{TH}$ the received signal,

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \begin{bmatrix} H_1^{DL} \\ H_2^{DL} \\ H_3^{DL} \end{bmatrix} Q^H x^{TH} + \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix}$$

$$= \begin{bmatrix} l_{11} & 0 & 0 \\ l_{21} & l_{22} & 0 \\ l_{31} & l_{32} & l_{33} \end{bmatrix} \begin{bmatrix} x_1^{TH} \\ x_2^{TH} \\ x_3^{TH} \end{bmatrix} + \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} \quad (22)$$

As $x_1^{TH} = \tilde{x}_1$, the received signal of second user is [3,p-415],

$$y_2 = l_{21} x_1^{TH} + l_{22} x_2^{TH} + z_2$$

$$= l_{21}\tilde{x}_1 + l_{22} x_2^{TH} + z_2$$

$$= l_{21}\tilde{x}_1 + l_{22}\left(\tilde{x}_2 - \frac{l_{21}}{l_{22}} x_1^{TH} + 2A.m_2 + j2A.n_2\right) + z_2$$

$$= l_{22}\left(\tilde{x}_2 + 2A.m_2 + j2A.n_2\right) + z_2 \quad (23)$$

Defining $\tilde{y}_2$ as a scaled version of y_2 we can write,

$$\tilde{y}_2 = \frac{y_2}{l_{22}} = \left(\tilde{x}_2 + 2A.m_2 + j2A.n_2\right) + \frac{z_2}{l_{22}} \quad (24)$$

The second-user signal $\tilde{x}_2$ can be detected with the modular operation,

$$\hat{\tilde{x}}_2 = \text{mod}_A(\tilde{y}_2) = \tilde{y}_2 - 2A(m_2 + jn_2) = \tilde{x}_2 + \frac{z_2}{l_{22}} \quad (25)$$

The received signal for third user is,

$$y_3 = l_{31} x_1^{TH} + l_{32} x_2^{TH} + l_{33} x_3^{TH} + z_3$$

$$= l_{31} x_1^{TH} + l_{32} x_2^{TH} + l_{33}\left(\tilde{x}_3 - \frac{l_{31}}{l_{33}} x_1^{TH} - \frac{l_{32}}{l_{33}} x_2^{TH} + 2A.m_3 + j2A.n_3\right) + z_3$$

$$= l_{33}\left(\tilde{x}_3 + 2A.m_3 + j2A.n_3\right) + z_3 \quad (26)$$

Like second user symbol, third-user signal $\tilde{x}_3$ can be detected with the modular operation,

$$\hat{\tilde{x}}_3 = \text{mod}_A(\tilde{y}_3)$$

Where $\tilde{y}_3$ is the scaled value of y_3,

$$\tilde{y}_3 = \frac{y_3}{l_{33}} = \left(\tilde{x}_3 + 2A.m_3 + j2A.n_3\right) + \frac{z_3}{l_{33}} \quad (27)$$

$$\text{So, } \hat{\tilde{x}}_3 = \tilde{y}_3 - 2A(m_3 + jn_3) = \tilde{x}_3 + \frac{z_3}{l_{33}} \quad (28)$$

The above mentioned broadcast channel techniques are used to remove the interference in the communication system. Dirty Paper Coding is a technique of precoding the data effect the interference can be canceled to some interference that is known to the transmitter. Tomlinson-Harashima Precoding (THP) in Decision Feedback Equalization (DFE) is to cancel the post-cursor ISI in the transmitter, where the past transmits symbols are known without possibility of errors.

4. Simulation and Results

Let us simulate transmission methods discussed in previous section with different number of users to analyse the bit error rate (BER) against the signal to noise ratio SNR[dB]. BER of each simulation is calculated using,

$$BER = \frac{1}{N_b L_b} \sum_{k=1}^{N_b} b_{err,k}$$

Where N_b is the number of simulated packets, L_b is the number of transmitted bits per packet k and $b_{err,\ k}$ is the number of erroneous bit per packet.

We first simulate channel inversion method with different number of active users and find that, with the increase of number of active users, bit error rate increases. This is because of the increase of interferences due to the other signals. Additional active user causes new channels for transmission which cause signal interferences and introduces noise to the signals.

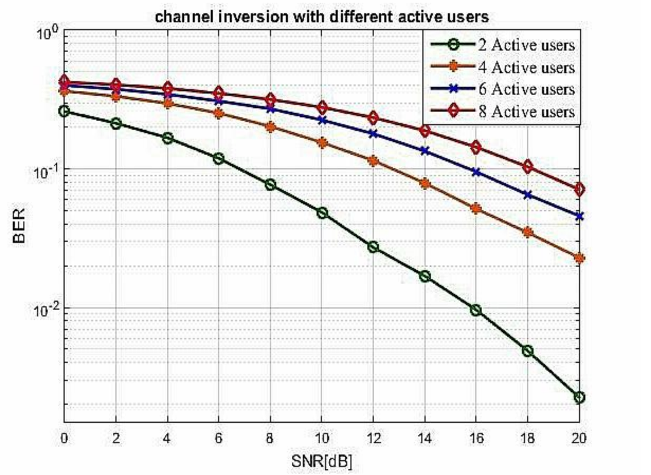

Figure 2: Channel Inversion with increasing number of users

Fig 2 illustrates the simulation result where bit error rate is lowest when active user is lowest. With the increase of active users, the bit error rates also increase and we see a high bit error rate when there are 8 active users.

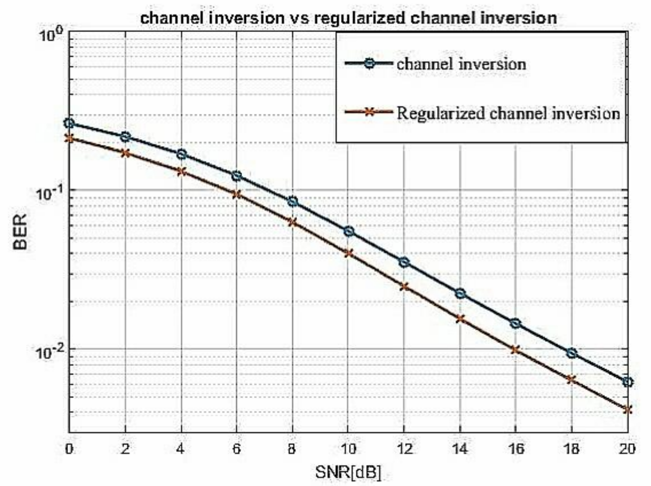

Figure 3: Channel inversion vs regularized channel inversion

In Figure 3, the BER performance of channel inversion is compared to that of regularized channel inversion for $N_B = 4$ and $N_M=1$, in which four users with the highest channel norm values are selected out of K = 10. Regularized channel inversion achieves better performance than channel inversion method. Channel inversion cancelled out the channel interference but cannot mitigate the noise enhancement which is done in Regularized channel inversion by using a pre-equalizing MMSE.

DPC schemes use the channel state information (CSI), available at the transmitter by means of feedback, and the a priori known users' data to eliminate or reduce the co-channel interference (CCI). The number of available transmit antennas should be larger than or equal to the total number of receive antennas at the mobile stations (MSs).

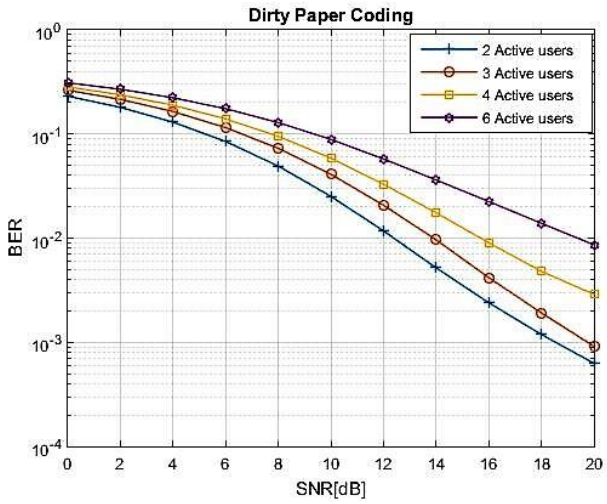

Figure 4: Dirty paper coding response with increasing number of users

Figure 4 shows the simulation of dirty paper coding with variable transmit antennas and variable active users. We use combinations of 4 Tx for 4 users, 5 Tx for 5 users, 6 Tx for 6 users, 7 Tx for 7 users and get the lowest BER for 4 Tx and 4 users.

From figure 4 we see that when active user number is lower the bit error rate is lower as inter-channel interference is lower. As number of active users is increased BER also increases at the same SNR and with the increase of SNR, BER gets lower.

Tomlinson Harashima precoding expands the data symbol by adding 2A.m with data symbol to reduce the peak or average power. TH precoding reduces the peak or average power in the decision feedback equalizer (DFE), which suffers from error propagation. Tomlinson Harashima Precoding cancels out the post cursor ISI.

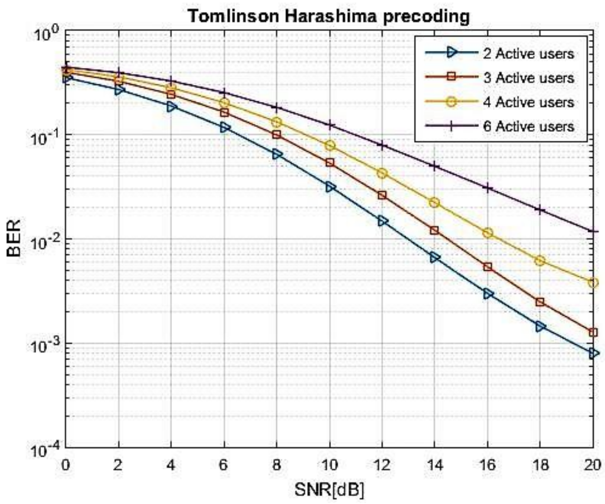

Figure 5: TH precoding with different number of users

Figure 5 shows the simulation of dirty paper coding with variable transmit antennas and variable active users. We use combinations of 4 Tx for 4 users, 5 Tx for 5 users, 6 Tx for 6 users, 7 Tx for 7 users and get the lowest BER for 4 Tx and 4 users.

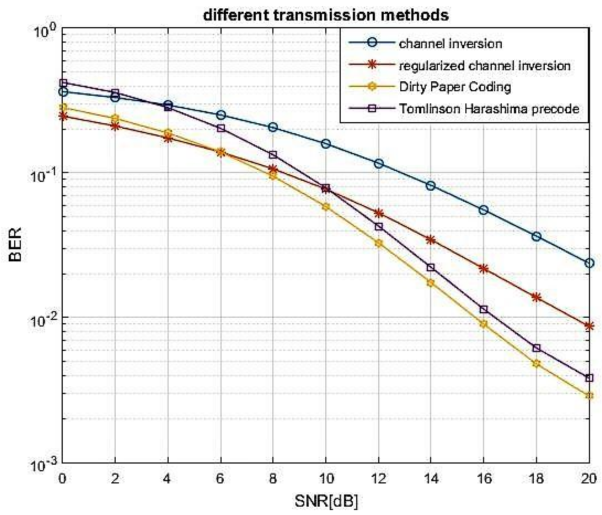

Figure 6: Comparison between methods of transmission

Figure 6 illustrates the comparison between all the transmission methods for broadcast channel where number of active users were 4, NB =4, k=10 and each user with NM =1.

Fig 6 illustrates that for very low SNR (< 4) regularized channel inversion has the lowest Bit error rate, when the SNR is increased, Dirty Paper Coding outperforms all other methods. Tomlinson Harashima Pre-coding has almost the same result as Dirty Paper Coding but with a little higher bit error probability. The only advantage of Tomlinson Harashima pre-coding over Dirty Paper Coding is the peak transmitted power is lower than Dirty Paper Coding. Channel inversion has the highest bit error probability among these 4 methods because of the channel's high noise enhancement. Regularized channel inversion reduces this noise enhancement and get a lower bit error rate.

5. Conclusion

From the discussion and the simulation results we find that increase of number of active users in a system makes the system complex and interferences. Due to these interferences error bits are present in the received signal. So the quality is degraded. System with lower active users have better performance. BER also depends on signal to noise ratio (SNR). With the increase of signal power performance of a system improves. Dirty Paper Coding and Tomlinson Harashima Precoding both have better performance. Like DPC, TH precoding has the similar BER response to increasing user. But here the BER is a little higher with respect to SNR. The average power or transmitted power of THP is lower than DPC and it is due to the modulo operation in the pre-coding process.

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