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**Article** *in* Research Journal of Applied Sciences, Engineering and Technology · August 2012



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Research Journal of Applied Sciences, Engineering and Technology 4(15): 2489-2495, 2012
ISSN: 2040-7467

Submitted: March 10, 2012 Accepted: March 22, 2012 Published: August 01, 2012

# Efficient PA-SLNR Linear Precoding For Multiuser Multiple Input Multiple Output System

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**Abstract:** In this study, linear precoding scheme for Multi-User Multiple Inputs Multiple Outputs (MU-MIMO) system is introduced. The Proposed method optimizes Per-Antenna Signal to Leakage Plus Noise Ratio (PA-SLNR) criteria and make use of Fukunaga-Koontz Transforms (FKT) computation to develop simple precoding algorithm. However, the linear technique available in the literature so far use Per-User Signal to Leakage plus Noise Ratio (PU-SLNR) and develop closed form precoding matrix solution based on Generalized Eigenvalue Decomposition (GEVD), the precoding matrix computation using GEVD gives poor results at high SNR values. Moreover, the PU-SLNR objective function neglects to take the intra-user antennas interference cancellation into account. In this study, a new cost function based on PA-SLNR is defined, FKT based solution is explained and novel simple algorithm is developed to compute the precoding matrices for multiple users of multiple antennas. The developed FKT transform algorithm reduces the overall computational load by removing the redundant computations of FKT transform factor for each receive antenna.

**Keywords:** Fukunaga-Koontz Transform (FKT), Generalized Eigenvalue Decomposition (GEVD), Multi-User Multiple Input Multiple Output (MU-MIMO), Per-Antenna Signal to Leakage Plus Noise Ratio (PA-SLNR), precoding

## INTRODUCTION

Multi-user multiple input multiple output Broadcast channel (MU-MIMO-BC) precoding design has received considerable attention in last decade (Wange *et al*., 2010; Khalid and Speidel, 2010; Sharma and Lambotharan, 2006). This high consideration is due to the high expected performance gain by using both MIMO and multiuser spatial dimensions. In the literature, due to the implementation complexity of nonlinear precoding methods (Lee and Jindal, 2006; Wei *et al*., 2001; Yinghang *et al*., 2011), several linear precoding designs methods were proposed. In these linear precoding methods, both joint and independent optimizations techniques were used to mitigate the Multi-User Interference (MUI) (Sadek *et al*., 2007a, b; Spencer *et al*., 2004; Stankovic and Haardt, 2008; Tenenbaum and Adve, 2009). Given that the channel state information is available at the transmitter and receiver, various conditions and objectives were used to study this problem. In L.S. and Zhang (2011), Spencer *et al*. (2004) and Stankovic and Haardt (2008) closed form solutions based on Minimum Mean Square Error (MMSE) were proposed. The method in Spencer *et al*. (2004) impose dimensionality restrictions that the number of base stations antennas should be greater than or equal to the total numbers of receive antennas for all users. On the other hand the method in Stankovic and Haardt (2008) relaxes the dimensionality constraint but with some performance loss at high SNR values when the total number of receive antennas of all users exceed the number of base station antennas. In Schubert *et al*. (2005), Shuying *et al*. (2008) and Tenenbaum and Adve (2009) an iterative Sum Mean Square Error (SMSE) method (joint transceiver design) were developed to compute both the precoding and decoding matrices. In spite of the high performance of these methods, complexity and restriction on the number of antennas are the main demerits of these methods. In Sadek *et al*. (2007a) beam-forming precoding design utilizing Per-User Signal to Leakage and Noise Ratio (PU-SLNR) cost function criteria was proposed. In this method, the precoding vectors for all users were obtained by solving a series of optimization problems using Generalized Eigenvalue Decomposition (GEVD). In Sadek *et al*. (2007b) PU-SLNR precoding matrix design based on GEVD for MU-MIMO spatial Multiplexing is proposed. This study shows that the precoding matrix computation using GEVD is simple but sensitive to singularity in the leakage plus noise power matrix, thus its performance is low at high SNR values. Consequently, Generalized Singular Value Decomposition (GSVD) and Fukunaga-Koontz Transforms (FKT) based computations

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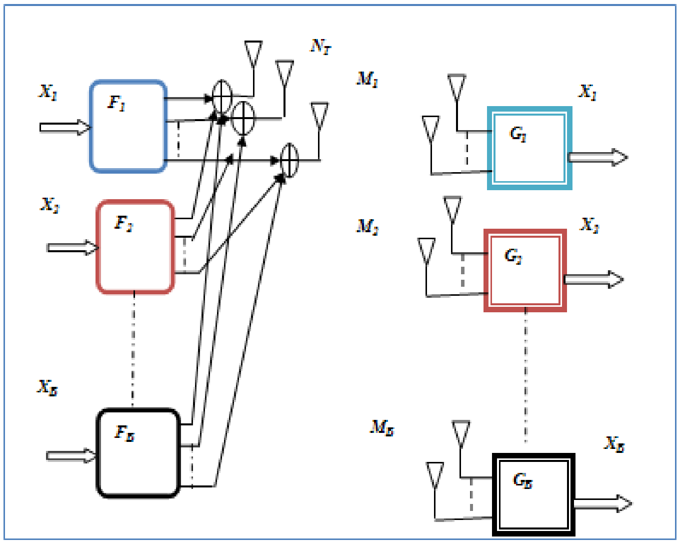


Fig. 1: MU-MIMO broadcast system block diagram

were utilized in Jaehyun *et al*. (2009) and Saeid *et al*. (2011) to solve the singularity in the matrix computation. The precoding design based on PU-SLNR cost function introduced in Sadek *et al*. (2007b) and Saeid *et al*. (2011) totally neglects to take into account the interference between streams multiplexed to one user (intra-user antenna interference). In this study, new cost function based on Per-Antenna Signal to Leakage plus Noise Ratio (PA-SLNR) criteria is proposed to account for inter antenna interference cancelation. Furthermore, Fukunaga-Koontz Transforms (FKT) based transformation is utilized to develop the precoding algorithm. Using both BER and received SINR outage as performance criteria, simulation result shows that the combination of the proposed PA-SLNR optimization method and the FKT computation approach generate numerically better results. The FKT is a matrix whitening transform that firstly developed in Fukunaga and Koontz (1970) and soon after used in many signal processing applications such as Linear Discriminant Analysis (LDA) (Cao and Haralick, 2007; Miranday and Whelan, 2005; Sheng and Sim, 2007; Zhang and Sim,2006). For example in (Zhang and Sim, 2006) FKT is used to resolve the singularity problem in LDA by avoiding matrix inversion process. In this study, FKT is used to solve the singularity problem in the computation and to reduce multiple user precoding matrices computational cast.

The superscripts $Q^T$, $Q^H$ are denoting the transpose and the congregate transpose of matrix $Q$, respectively. $tr(Q)$ and $\|Q\|^2_F$ are denoting the trace and Frobenious norm respectively. $rank\,(Q)$ denotes the rank of the matrix $Q$ . $I_{NT}$ is an $N_T \times N_T$ identity matrix. D = $diag\ \{\lambda_1\lambda_2\ldots \lambda_r\}$, denotes a diagonal matrix with diagonal elements$\{\lambda_1\lambda_2\ldots\ \lambda_r\}$.

**Mu-mimo broadcasting system model**: We consider a downlink MU-MIMO broadcast channel with central node Base station/ Access point communicating with $B$ users simultaneously in the same time and frequency. The central node base station is equipped with $N_T$ transmit antennas and each individual user $k$ is equipped with $M_k$ receive antennas, $k = 1,..., B$ as shown in Fig. 1. The central node spatially multiplexes and sends $B$ data vectors to the $B$ number of users simultaneously. We assume perfect Channel State Information (CSI) is available at both the transmitter and receiver.

The channel from the central node to each user is assumed to be frequency flat fading and constant over all transmission block duration. The element of any user channel $H_k \in C^{M_k \times N_T}$ is assumed to be complex Gaussian variables with zero mean and unit-variance. The combined channel matrix for all $B$ number of users in the system is given by:

$$\mathrm{H}_{\mathrm{com}} = [\mathrm{H}_1^{\mathrm{T}}\mathrm{H}_2^{\mathrm{T}} \ldots. \mathrm{H}_{\mathrm{B}}^{\mathrm{T}}]^{\mathrm{T}} \tag{1}$$

the received signal at the $k^{th}$ user is given by:

$$\mathrm{y}_{\mathrm{k}} = H_k F_k x_k + \sum_{\substack{i=1 \\ i \neq k}}^{B} F_i x_i + n_k \tag{2}$$

where, $F_k \in C^{N_T \times M_k}$ is the $k^{th}$ user precoding matrix while $x_k \in C^{M_K \times 1}$ is the $k^{th}$ user data vector. The entries of received noise vector $n_k$ are assumed to be independent complex Gaussian variables with zero-mean and variance equal to $\sigma^2_k$. Also we assume that the noise variances at all antenna elements as well as the noise at the all users are equal. Thus, $\sigma^2_1 = \sigma^2_2 \; \ldots = \sigma^2_{M_k}$. The entries of the $M_k \times N_T$ channel $H_k$ are described by:

$$H_k = \begin{bmatrix} h_k^{(1,1)} & \cdots & h_k^{(1,N_t)} \\ \vdots & \ddots & \vdots \\ h_k^{(M_k,1)} & \cdots & h_k^{(M_k,1)} \end{bmatrix} \in C^{(M_k \times N_T)} \qquad (3)$$

also we assume that for any $k^{th}$ user, the data vector $x_k$ and the precoding matrix $F_k$ are normalized such as that:

$$E\left\|x_k\right\|_f^2 = I_{M\,k}; tr\left(F_k F_k^H\right) = 1$$
$$for\;\; k = 1, \ldots, B \qquad (4)$$

and for each $k^{th}$ individual user, the decoding matrix $G_k$ is constructed at the $k^{th}$ user terminal to decode the received signal.

**Successive pa-slnr maximization precoding:** The objective function originally proposed in Sadek *et al*. (2007a)maximizes the SLNR of each user. Thus, the precoder designed cancels only the inter-user interference. This study, however, propose new cost function that maximizes the SLNR for each individual receive antenna (PA-SLNR) which would help to minimize inter-antenna interference and thus result in a better precoder that maximizes the overall SLNR per user more efficiently. This is justified because PA-SLNR as explained in Fig. 2 takes into account the intera-antenna interference. For each $k^{th}$ user $j^{th}$ receive antenna,The $PA - SLNR^j_k$, $y^i_k$,is defined as ratio between the individual $j^{th}$received antenna desired signal power to the interference introduced by the $j^{th}$ receiving antenna to all other antennas plus the noise power at the $j^{th}$ receiving antenna front end. So, for the $k^{th}$ user, $j^{th}$ receive antenna, the signal to leakage plus noise ratio $\gamma^j_k$ is given by:

$$\gamma_k^i = \frac{\left\|\hbar_k^j f_k^j\right\|_F^2}{\sum_{\substack{i=1\\i\neq k}}^{B} \left\|H_i f_k^j\right\|_F^2 + \sum_{\substack{i=1\\i\neq j}}^{M_k} \left\|\hbar_k^j f_k^j\right\|_F^2 + \sigma^{2\,j}_{\;k}} \qquad (5)$$

where, $\hbar_k^j \in C^{1\times N_T}$ is the $k^{th}$ user, $j^{th}$ antenna received row vector. If we define an auxiliary matrix $\tilde{\hbar}_k^j$ as the matrix contains all the $k^{th}$ user receive antenna row vectors except the $j^{th}$ antenna row vector as follows:

$$\tilde{\hbar}_k^j = \begin{bmatrix} h_k^{(1,1)} & h_k^{(1,2)} & \cdots & h_k^{(1,N_T)} \\ \vdots & \vdots & \vdots & \vdots \\ h_k^{(i-11)} & h_k^{(i-12)} & \cdots & h_k^{(j-1,N_T)} \\ h_k^{(i+11)} & h_k^{(i+12)} & \cdots & h_k^{(j+1,N_T)} \\ \vdots & \vdots & \vdots & \vdots \\ h_k^{(M_k,1)} & h_k^{(M_k,2)} & \cdots & h_k^{(M_k,N_T)} \end{bmatrix} \in C^{((M_k-1)\times N_T)} \qquad (6)$$

And the combined channel matrix for all other system received antennas except the $j^{th}$ desired receive antenna as:

$$\tilde{H}_k^j = \left[\tilde{\hbar}_k^{j^T} H_1^T \ldots H_{k-1}^T H_{k+1}^T \ldots H_B^T\right]^T \qquad (7)$$

Then from Eq. (6) and (7), the expression in (5) can be reduced to:

$$\gamma_k^j = \frac{\left\|\hbar_k^j f_k^j\right\|_F^2}{\left\|\tilde{H}_k^j f_k^j\right\|_F^2 + \sigma^{2\,j}_{\;k}} \qquad (8)$$

**Problem statement:** For any $j^{th}$ receive antenna at the $k^{th}$ user, select the precoding vector $f^j_k$, where k = {1, …, $B$}, $j$ = {1, … , $M_k$} such that the per-antenna signal to leakage plus noise ratio $y^i_k$ is maximized:

$$f_k^j \arg \max_{f_k^j \in C^{N_T\times 1}} \frac{f_k^{j^H} (\hbar_k^{j^H} \hbar_k^j) f_k^j}{f_k^{j^H} (\tilde{H}_k^{j^H} \tilde{H}_k^j + \sigma_{vk}^{2^j} I_{N_T}) f_k^j}$$
$$Subject\;\; to$$
$$tr(F_k F_k^H) = 1$$
$$F_k = [f^1, \ldots, f^{M_k}] \qquad (9)$$

The optimization problem in Eq. (9) deals with the $j^{th}$ antenna desired signal in the numerator and a combination of total leaked power from the $j^{th}$ antenna to all other antennas plus noise power at the $j^{th}$ antenna front end in the denominator. To calculate the precoding matrix for each user we need to calculate the precoding vector for each receive antenna independently. This requires solving the linear fractional optimization problem in Eq. (9) $M_k$ times and consequently $M_k \times B$ times for all users by using either GEVD (Sadek *et al*., 2007a) or GSVD(Park *et al*., 2009) which lead to high computational load at the base stations. In the next section, FKT transform based solution method for solving such series of linear fractional optimization problems is described and simple computational method for MU-MIMO precoding algorithm is developed.

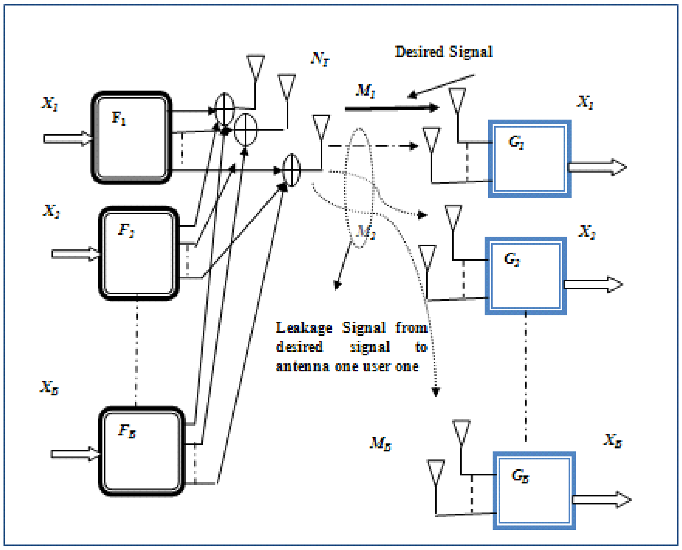


Fig. 2: System model depicting all variables

**The fkt based precoding algorithm:** Researchers in Sheng and Sim (2007) and Zhang and Sim (2006) formulate the problem of two classes recognitions problem as follows: given the data matrices $\psi_1$ and $\psi_2$ from the two classes, the corresponding autocorrelation matrices $\Re_1 = \psi_1 \psi^T_1$ and $\Re_2 = \psi_2 \psi^T_2$ are positive simi-definite (p.s.d) and symmetric. For any given p.s.d autocorrelation matrices $\Re_1$ and $\Re_2$ the sum of these two matrices i.e., $\Re$ is still p.s.d and can be written as:

$$\Re = \Re_1 + \Re_2 = \left[UU_\perp\right]\begin{bmatrix} D & 0 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} U^T \\ U^T_\perp \end{bmatrix} \tag{10}$$

Without loss of generality, the sum $\Re$ can be singular and consequently, the value $r = rank(\Re) < Dim.$ where $r$ is related to $\Re$ by $D = diag(\lambda_1, \ldots \lambda_r)$ with $\lambda_1 \geq \ldots \geq \lambda_r > 0$. $Dim.$ is the length of vector in $\Re$ .$U \in C^{Dim \times r}$ is the set of eigenvectors that corresponds to the set of nonzero eigenvalues and $U_\perp \in C^{Dim \times (Dim-r)}$ is the orthogonal complement of $U$. From Eq. (10), the FKT transform operator is defined as:

$$p = UD^{-½} \tag{11}$$

By using this FKT transform factor, the sum p.s.d matrix $\Re$ can be whitened such that the whitening two Sub-matrices matrices $\Re_1$ and $\Re_2$ is equal to the identity matrix as follows:

$$P^T \Re p = p^T(\Re_1 + \Re_2)p = \tilde{\Re}_1 + \tilde{\Re}_2 = I^{r\times r} \tag{12}$$

where: $\tilde{\Re}_1 = p^T \Re_1 p, \tilde{\Re}_2 = p^T \Re_2 p$, are the transformed covariance matrices $\Re_1$ and $\Re_2$ respectively and $I^{r\times r}$ is an identity matrix. Suppose that $v$ is an eigenvector of $\Re_1$ with corresponding eigenvalue $\lambda_1$, then $\tilde{\Re}_1 v = \lambda_1 v$ and since from Eq. (12), $\tilde{\Re}_1 = I - \tilde{\Re}_2$ thus, the following results can be pointed out:

$$(I - \tilde{\Re}_2)v = \lambda_1 v \tag{13}$$

and consecquently

$$\tilde{\Re}_2 v = (1 - \lambda_1)v \tag{14}$$

which means that $\tilde{\Re}_2$ has the same eigenvectors as $\tilde{\Re}_1$ with corresponding eigenvalues related as $\lambda_2 = (1-\lambda_1)$. Thus, we can concludes that the dominant eigenvectors of $\tilde{\Re}_1$ is the weakest eigenvectors of $\tilde{\Re}_2$ and vice versa. Based on this FKT transform analysis we conclude that the transformed matrices $\tilde{\Re}_1$ and $\tilde{\Re}_2$ share the same eigenvectors and the sum of the two corresponding eigenvalues are equal to one. Thus we summaries the following results:

$$\tilde{\Re}_1 = V\Lambda_1 V^T \tag{15}$$

$$\tilde{\Re}_2 = V\Lambda_2 V^T \tag{16}$$

$$I = \Lambda_1 + \Lambda_2 \tag{17}$$

where: $V \in C^{r \times r}$ is the matrix contains all the eigenvectors and $\Lambda_1, \Lambda_2$ are the corresponding eigenvalues matrices. Thus, from these analyses we conclude that FKT gives the best optimum solution of any fractional linear problem without going through any serious matrix inversion step.

By relating FKT transform analysis of the two covariance data matrices and the precoding design problem for MU-MIMO (multiple linear fractional optimization problems) and making direct mapping of the optimization variable from Eq. (9) to the FKT transform such as:

$$\Re_1 = \hbar^{j\,H}_k \hbar^j_k \tag{18}$$

$$\Re_2 = \tilde{H}^{j\,H}_k \tilde{H}^j_k + \sigma^j_k I_{N_T} \tag{19}$$

and consequently the sum $\Re$ of the two covariance matrices becomes:

$$\Re = H^H_{com} H_{com} + \sigma^j_k I_N \tag{20}$$

According to FKT analysis, we can use Eq. (11) to calculate the FKT factor and consequently we use this transformation factor to generate the shared eigenspace matrices $\tilde{\Re}_1$ and $\tilde{\Re}_2$ using the facts from Eq. (12)-(14) for each receive antenna in the system. The shared Eigen subspaces are complement of each other's such that the best principle eigenvectors of the first transformed covariance matrix $\tilde{\Re}_1$ is the least principle eigenvector for the second transformed covariance matrix $\tilde{\Re}_2$ and vice-versa. Thus, we can calculate the receive antenna precoding vector by simply multiply FKT factor with the eigenvectors correspond to best eigenvalue of the transformed antenna covariance matrix or eigenvector that corresponding to the least eigenvalue of the transformed leakage plus noise covariance matrix. The most notable observation is that for the set of $M_k \times B$ receive antennas in the system, we need to compute the FKT transform factor one time only, which cuts down the computation load sharply. Algorithm .1, summarizes the steps to compute the precoding matrix for multiple $B$ users in the system,

**Algorithm 1:** PA-SLNR MU-MIMO precoding based on FKT for multiple B independent MU-MIMO users.

**Input:** all B users combined channel matrix and the received noise variance. $H_{com} = [H^T_1 H^T_2 \dots H^T_B], \sigma^{2j}_k$

Output: multiple B users precoding matrices $F_k$ such that, k = 1 ,… ,B

Compute the sum $\Re = H^H_{com} H_{com} + \sigma^j_k I_{NT}$

Compute FKT factor $P = UD^{-1/2}$ from SVD ($\Re$)

For k = 1 to B

For j =1 to $M_k$

Transform the j<sup>th</sup> receive antenna covariance matrix $\Re_1$ (equation 18)using the FKT factor

P to $\tilde{\Re}_1$ and select the first eigenvecto $V^j_k$ r of $\tilde{\Re}_1$

The precoding vector correspond to the $j^{th}$ receive antenna at the $k^{th}$ user is $f^j_k = P\, v^j_k$

End

The kt<sup>h</sup> user precoding matrix is $F_k = [f^1_k \dots f^{M_k}_k]$

End

The algorithm takes the combined MU-MIMO channel matrix as well as the value of the noise covariance as inputs and outputs $B$ users precoding matrices. It computes the FKT Factor in steps one and two and iterates $B$ times from step three to six to calculate the precoding matrices for $B$ multiple users. For each user there are $M_k$ sub-iteration operations from step four to five to calculate any $k^{th}$ user precoding matrix vector by vector.

## SIMULATION AND RESULTS

The performance of the proposed MU-MIMO precoder is measured in terms of the average received BER and output received SINR outage. We evaluate and compare the performance of the proposed *PA-SLNR* MU-MIMO precoding scheme based on FKT algorithm through Monte-Carlo simulation for different MU-MIMO-BC system configurations. In each simulation setup, the entry of each $k^{th}$ user MIMO channel $H_k$ is generated as complex white Gaussian entries with zero mean and unit variance. In all simulations, each user data symbols vector is 4-QAM modulated and spatially multiplexed at the base station. At the receivers, matched filter is used to decode each user's data.

Figure 3, compares the average received BER performance of the proposed *PA-SLNR* precoding which denoted in figure By *PA-SLNR-FKT* and the reference literature results of *SLNR-GSVD* (Jaehyun *et al*., 2009) as well as *SLNR-GEVD*(Sadek *et al*., 2007b) precoding schemes for the MU-MIMO-BC system configurations of $N_T = 12$ , $B = 3$ , $M_k = 4$.In this full rate MU-MIMO configuration, the base station modulates, spatially multiplexes and precodes a vector of length 4 symbols to each user. The average BER is calculated over 2000 MU-MIMO channel realization for each algorithm. The proposed method outperforms both *SLNR-GEVD* and *SLNR-GSVD*. At BER equal to $10^{-2.8}$ there is approximately 6 dB performance gain between *PA-SLNR-FKT* and *SLNR-GSVD.*

Figure 4, compares the average received BER performance of the proposed *PA-SLNR-KFT* and the literature reference methods *SLNR-GSVD* and *SLNR-GEVD* precoding schemes for the MU-MIMO-BC channel system configurations of $N_T = 10$ , $B = 3$ , $M_k = 3$. In this configuration, the number of the base stations' antennas is more than the sum of all receive antenna which signify more degree of freedom in MU-MIMO transmission. In this configuration, the base station

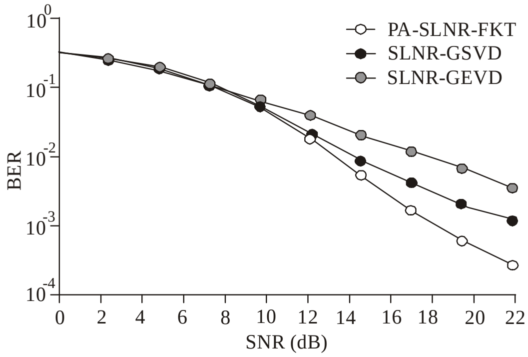


Fig. 3: Shows the compression of the un-coded BER performance for PA-SLNR-FKT, SLNR-GSVD and SLNR-GEVD precoding methods under system configuration of $B = 3$, $M_k = 4$, $N_T = 12$, 4-QAM modulated signal

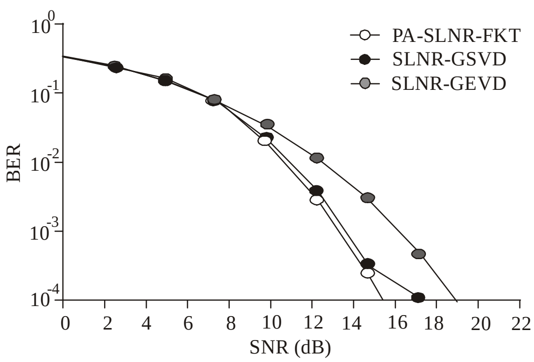


Fig. 4: Shows the compression of the un-coded BER performance for PA-SLNR-FKT, SLNR-GSVD and SLNR-GEVD precoding methods under system configuration of $B = 3$, $M_k = 3$, $N_T = 10$,4-QAM modulated signal

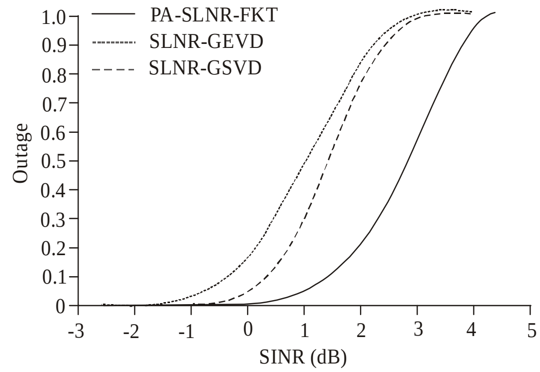


Fig. 5: Shows the comparison of the output SINR outage performance PA-SLNR-FKT, SLNR-GSVD and SLNR-GEVD precoding methods under system configuration of $B = 3$, $M_k = 4$, $N_T = 12$, 4-QAM modulated signal at 2 dB input SNR

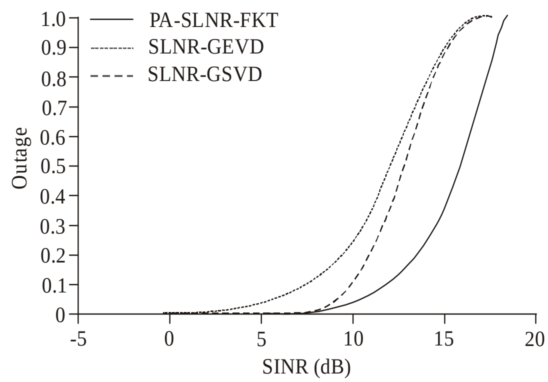


Fig. 6: Shows the comparison of the output SINR outage performance PA-SLNR-FKT, SLNR-GSVD and SLNR-GEVD precoding methods under system configuration of $B = 3$, $M_k = 4$, $N_T = 12$, 4-QAM modulated signal at 8dB input SNR

modulates, spatially multiplexes and precedes a vector of length 3 symbols to each user. The average BER is calculated over 2000 MU-MIMO channel realization for each algorithm. The proposed method outperforms *SLNR-GSVD* and *SLNR-GEVD.* At BER equal to $10^{-4}$ there is approximately 2 dB performance gain between *PA-SLNR-FKT* and *SLNR-GSVD.* The performance gain between *PA-SLNR-FKT* and *SLNR-GSVD* is very small compared with full rate configuration because the MU-MIMO configuration used in the simulation has more degrees of freedom.

Figure 5, compares the received output SINR outage performance of the proposed PA-SLNR-FKT precoding and the reference SLNR-GSVD and SLNR-GEVD precoding methods. MU-MIMO system configuration of $B = 3$ , $M_k = 4$, $N_T = 12$ and 2dB input SNR is considered in the simulation. The proposed method outperforms the SLNR-GSVD method by 1 dB gain at 10% received output SINR outage.

Figure 6, compares the received output SINR outage performance of the proposed PA-SLNR-FKT precoding and the reference SLNR-GSVD and SLNR-GEVD precoding Methods. MU-MIMO system configuration of $B = 3$ , $M_k = 4$, $N_T = 12$ and 8dB input SNR is considered in the simulation. The proposed method outperforms the SLNR-GSVD method by approximately 1.5 dB gain at 10% received output SINR outage.

## CONCLUSION

In this paper, New MU-MIMO precoding method based *PA-SLNR criteria* is proposed and simple algorithm based on FKT is developed. Unlike the conventional literature methods which neglect to take into account the individual user inter-antenna interference cancelation, the proposed method transforms the MU-MIMO channel into a set of single antenna channels to effectively cancel inter-antenna interference and multiplex multiple data stream to each user. Simulation results show that the proposed Method outperforms the conventional Per-user SLNR-GSVD and SLNR-GEVD precoding methods.

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