Subspace Optimized-based Interference Alignment and Interference Cancelling Block Modulation

A Project Report

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THESIS CERTIFICATE

This is to certify that the thesis titled Subspace Optimized-based Interference Alignment and Interference Canceling Block Modulation, submitted by **K Satyanarayana**, to the Indian Institute of Technology, Madras, for the award of the degree of **Bachelor of Technology**, is a bona fide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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I owe a lot more than words of gratitude to my family, who constantly supported me through the most difficult of times. Thank you.

ABSTRACT

This thesis is organized in two parts. In the first part of the thesis, we study the *subspace optimized-based interference alignment transceiver design*for MIMO interference channel. For a given system model, the cores of the framework are the problem formulation of the interference alignment (IA) transceiver design based on the interference alignment's zero condition and the solution to the IA formulation function. The algorithm presented in this thesis maximizes the desired signal subspace, and also aligns the interference into the null space. Further, the simulations shows the convergence of the algorithm proposed, sum-rate and interference leakage. Also, simulations for minimizing the interference leakage are also provided.

In the second part of the thesis, we study the *interference canceling and block modulation (ICBM) scheme* for interference management in heterogeneous networks. ICBM model could be viewed as a solution for allocating resources and managing interference between various types of base stations. Specifically, our simulation results show that ICBM acts as a virtual resource, significantly improving the data rates for cell-edge users as well as the cell average throughput over the conventional techniques in typical interference scenarios arising in heterogeneous networks.

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ABBREVIATIONS

SNR	Signal to Noise Ratio
SINR	Signal to Interference plus Noise Ratio
BER	Bit Error Rate
DoF	Degrees of Freedom
QPSK	Quadrature Phase Shift Keying
ICBM	Interference Cancelling Block Modulation
AWGN	Additive White Gaussian Noise
ML	Maximum Likelihood
MD	Minimum Distance
SVD	Singular Value Decomposition
Tx	Transmitter
Rx	Receiver
dB	Decibel

NOTATION

A	Matrix
A^T	Transpose of a Matrix
$A^\dagger$	Hermitian Transpose of a Matrix
A^{-1}	Inverse of a Matrix
I_N	Identity Matrix
Log	Logarithm to the base 2
$\mathbb{C}$	Set of all Complex numbers
$\mathbb{R}$	Set of all Real numbers
$\mathbb{C}^{\mathbb{K}\times\mathbb{N}}$	Set of $K \times N$ matrices with complex entries
$\mathcal{CN}(\mu, \sigma^2)$	Complex Gaussian Distribution with mean μ and variance σ^2
T_j	j^{th} transmitter
R_j	j^{th} Receiver.

Part I

Iterative and Subspace Optimized-based Interference Alignment

CHAPTER 1

Introduction

In this chapter, an attempt is made to review, very briefly, the existing literature on interference alignment in general. The scope of the current work and the general outline of the first part of this report are presented.

1.1 Interference Alignment-A Literature Review

Interference alignment (IA) scheme is based on the degrees of freedom[1]. In IA, precoders are designed such that it maximize the degrees of freedom. The total degrees of freedom that can be achieved using IA schemes for K users is $K/2$. Based on IA the iterative interference alignment presented in [1] could be viewed as constructing the desired signal in such a way that, interference is aligned to one of half the signal subspace and leaving the other half with the desired signal, which is free of interference as shown in Fig. 1.1. However, precoders designed using interference alignment, and the algorithms such as iterative IA and subspace optimized-based interference alignment that are discussed in the report are for Gaussian alphabet signalling.

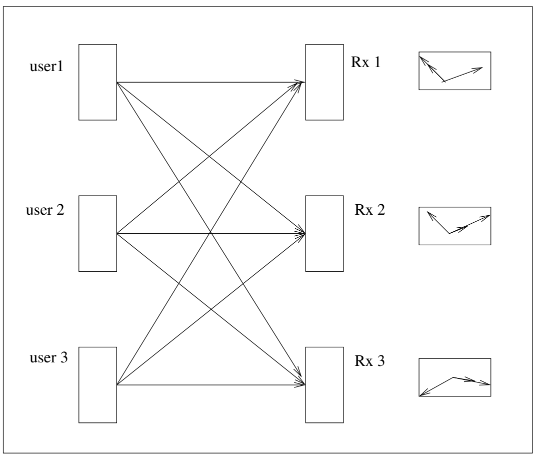

Figure 1.1: Interference Alignment: Arrows showing aligned interference and the desired signal.

[1] S. Jafar and S. Shamai, Degrees of freedom region for the MIMO X channel, arXiv:cs.IT/0607099v3, May 2007

Interference alignment presented in [1] to design the transmitting precoders is a closed form expression and requires the absolute knowledge of the channel state information (CSI) of all the transmitters. Obtaining the CSI has an overwhelming overhead in practice. Moreover, it was said in [1] and [2] that finding an analytical solution and the feasibility of interference alignment over a limited number of signalling dimensions is an open problem.

1.2 Scope of the Current Work

In this report, iterative interference alignment and subspace optimized based interference alignment are presented. The algorithms presented in this report does not require absolute channel state information as presented in [1]. It is required for the receiver to know only the local channel knowledge of the corresponding transmitter, and the co-variance matrix of the interference from all the other transmitters (users) and the AWGN. Precoding and decoding matrices are designed using algorithms like iterative interference alignment which minimize the interference leakage [2], and subspace optimized based interference alignment which maximize the SINR. Simulation results are presented to demonstrate the convergence of the algorithms and performance based on average sum rate.

1.3 Organization of this Part of the Report

In chapter 2, the system model, feasibility and reciprocity of interference alignment are outlined. Further in this chapter, algorithms and simulation results that are discussed in the report are presented. Also, comparison of the performance is also made on the sum rate and interference leakage between iterative and subspace optimized-based interference alignment.

CHAPTER 2

Subspace Optimized-based Interference Alignment

In this chapter, system model, feasibility and reciprocity of the alignment, and algorithms that are discussed in this report are presented.

2.1 System Model

We consider the K-user MIMO interference channel where the K^{th} transmitter and receiver are equipped with $M^{[K]}$ and $N^{[K]}$ antennas respectively. The receiver receives $d^{[k]}$ data streams from its corresponding transmitter and it only needs to correctly decode the corresponding signal. The received signal at the receiver k is expressed as

$$Y^{[k]} = U^{[k]} H^{[kk]} V^{[k]} S^{[k]} + \sum_{l=0, l \neq k}^{K} U^{[k]} H^{[kl]} V^{[l]} S^{[l]} + U^{[k]\dagger} Z^{[k]} \tag{2.1}$$

where $U^{[k]} \in C^{(N^{[k]} \times d^{[k]})}$ is the decoder matrix at the receiver k. $H^{[kl]} \in C^{(N^{[k]} \times M^{[l]})}$ is the channel matrix from transmitter l to the receiver k. The signal $S^{[k]}$ is with distribution $\mathcal{N}(0, \frac{P_k}{d_k})$, which is encoded using the precoder matrix $V^{[k]} \in C^{(M_k \times d_k)}$

2.2 Feasibility of Alignment

Given the channel matrices $H^{[kl]}$, we say that the degrees of freedom (DoF) [1], k $\in$ K allocation $(d^1, d^2, ..., d^k)$ is feasible if there exist transmit precoding matrices $V^{[k]}$ and receive interference suppression matrices $U^{[k]}$ [1].

$$V^{[k]} : M^{[k]} \times d^{[k]}, V^{[k]\dagger} V^{[k]} = I_d^{[k]} \tag{2.2}$$

$$U^{[k]} : N^{[k]} \times d^{[k]}, U^{[k]\dagger} U^{[k]} = I_d^{[k]} \tag{2.3}$$

[1] $d^k \leq min(M^{[k]}, N^{[k]}) k \in K$, denotes the degrees of freedom for user k's message.

such that

$$U^{[k]}H^{[kj]}V^{[l]} = 0, \forall l \neq k \tag{2.4}$$

$$rank(U^{[k]}H^{[kk]}V^{[k]}) = d_k, \forall k \in K \tag{2.5}$$

2.3 Reciprocity of Alignment

The duality relationship between interference channel and its reciprocal channel is obtained by switching the direction of communication, i.e., $\overleftarrow{V^{[k]}}, \overleftarrow{U^{[k]}}$ becomes the transmit precoding matrices and receive interference suppression matrices.

Feasibility Conditions on Reciprocity

The feasibility condition on the reciprocity are:

$$\overleftarrow{V}^{[k]} : N^{[k]} \times d^{[k]}, \ \overleftarrow{V}^{[k]\dagger}\overleftarrow{V}^{[k]} = I_d^{[k]} \tag{2.6}$$

$$\overleftarrow{U}^{[k]} : M^{[k]} \times d^{[k]}, \ \overleftarrow{U}^{[k]\dagger}\overleftarrow{U}^{[k]} = I_d^{[k]} \tag{2.7}$$

such that

$$\overleftarrow{U}^{[k]}\overleftarrow{H}^{[kk]}\overleftarrow{V}^{[l]} = 0, \forall l \neq k \tag{2.8}$$

$$rank(\overleftarrow{U}^{[k]}\overleftarrow{H}^{[kk]}\overleftarrow{V}^{[k]}) = d^{[k]}, \forall k \in K \tag{2.9}$$

Now, if we set $\overleftarrow{V}^{[k]} = U^{[K]}$ and $\overleftarrow{U}^{[k]} = V^{[k]}$, the feasibility condition would meet i.e., it is now identical to the earlier conditions.

2.4 Algorithms

If the interference is completely cancelled, then the received signal of user k is expressed as

$$Y^{[k]} = \hat{H}^{[kk]}S^{[k]} + \hat{Z}^{[k]} \tag{2.10}$$

where $\hat{Z}_k$ is an AWGN vector, the desired signal received at receiver k through channel matrix

$$\hat{H}_{kl} = U^{[k]]\dagger} H^{[kl]} V^{[l]} \tag{2.11}$$

and the rate achieved at the receiver k is

$$R^{[k]} = log \mid (I^{[d]} + \frac{P^{[k]}}{d_k} \hat{H}^{[kk]} \hat{H}^{[kk]\dagger}) \mid \tag{2.12}$$

The goal is to achieve the interference alignment by reducing the interference leakage or maximizing the signal to interference plus noise ratio. If the interference is not completely cancelled, then the interference plus noise leakage at the receiver k is given by

$$I^{[k]} = Tr(U^{[k]\dagger} Q^{[k]} U^{[k]}) \tag{2.13}$$

$$Q^{[k]} = \sum_{l=1, l \neq k}^{K} \frac{P^{[l]}}{d_l} H^{[kl]} V^{[l]} V^{[l]\dagger} H^{[kl]\dagger} + I_N^{[k]} \tag{2.14}$$

similarly, in the reciprocal network the interference plus noise leakage at receiver k due to all other unwanted transmitters is

$$\overleftarrow{I}^{[l*]} = Tr[\overleftarrow{U}^{[l]\dagger} \overleftarrow{Q}^{[l]} \overleftarrow{U}^{[l]}] \tag{2.15}$$

where

$$\overleftarrow{Q}^{[l]} = \sum_{l=1, l \neq k}^{K} \frac{\overleftarrow{P^{[k]}}}{d_k} \overleftarrow{H}^{[lk]} \overleftarrow{V}^{[k]} \overleftarrow{V}^{[k]\dagger} \overleftarrow{H}^{[lk]\dagger} + I_M^{[l]} \tag{2.16}$$

2.4.1 Algorithm for iterative interference alignment

Iterative algorithm alternates between the original and reciprocal networks. This follows in two steps. In the first step each receiver solves the following optimization problem

$$\min_{U^{[k]}: N^{[k]} \times d^{[k]}, U^{[k]} U^{[k]\dagger}} = I^{[k*]} \tag{2.17}$$

i.e., it minimize the leakage interference due to all undesired transmitters. The least interference is the space spanned by the $d^{[k]}$ smallest eigen values of the interference matrix $Q^{[k]}$. Thus $U^{[k]}$ has the column vectors corresponding to the $d^{[k]}$ smallest eigen vectors of $Q^{[k]}$.

$$U^{[k]} = v_d[Q^{[k]}], d = 1, 2, .., d^{[k]} \tag{2.18}$$

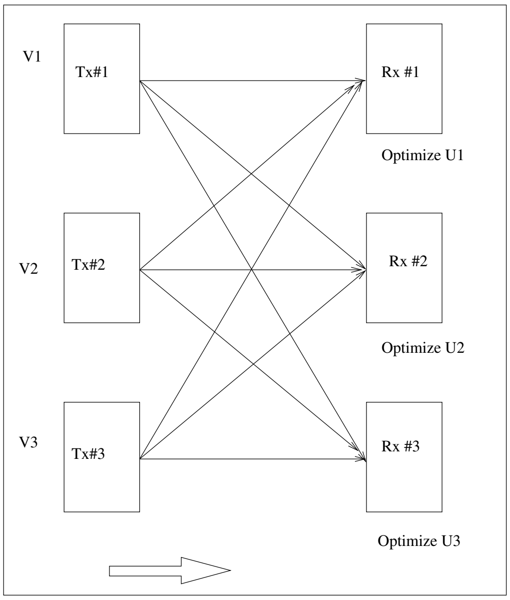

Figure 2.1: Showing communication direction for step 1 of algorithm

where $v_d[A]$ is the eigen vector corresponding to the d^{th} smallest eigen value of A.

The second step is identical to the first but performed in the reciprocal network. Using the reciprocity of alignment as discussed in the previous section, $\overleftarrow{V}^{[k]}$, $\overleftarrow{U}^{[k]}$ are the precoding and decoding matrices. Repeating the step 1 for the reciprocal network, we have the following optimization problem.

$$\min_{\overleftarrow{U}^{[l]}:M^{[l]}\times d^{[l]},\overleftarrow{U}^{[l]}\overleftarrow{U}^{[l]\dagger}} = I^{[l*]} \tag{2.19}$$

similar to step 1 the solution for $\overleftarrow{U}^{l}$ has the column vectors corresponding to the $d^{[l]}$ smallest eigen values of $Q^{[l]}$, i.e.,

$$\overleftarrow{U}^{[l]} = v_d[\overleftarrow{Q}^{[l]}], d = 1, 2, .., d^{[k]} \tag{2.20}$$

This is iterated till the algorithm converges. The Fig. 2.1 and Fig. 2.2 shows the pictorial representation of transmission with reciprocity. The convergence of the algorithm is shown in Fig. 2.3. It can be seen in Fig. 2.3 that as the number of iterations of the algorithm increases, the objective function that minimizes the interference leakage reduces and converges to a minimum value.

Convergence of the Algorithm: To prove the convergence of the algorithm, we introduce

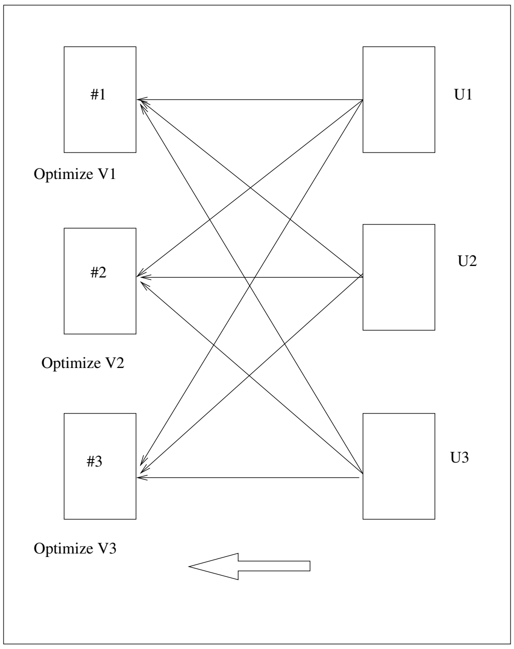

Figure 2.2: Reverse direction communication showing reciprocity for step 2 of algorithm

weighted leakage interference (WLI) as:

$$I_w = \sum_{k=1}^{K} \sum_{l=1, j \neq k} \frac{\overleftarrow{P^{[k]}}}{d^{[k]}} \frac{P^{[l]}}{d^{[l]}} Tr(U^{[k]\dagger} Q^{[k]} U^{[k]}) \tag{2.21}$$

WLI associated with receiver K is

$$I_w^{[k*]} = \frac{\overleftarrow{P^{[k]}}}{d^{[k]}} Tr(U^{[k]\dagger} Q^{[k]} U^{[k]}) = \frac{\overleftarrow{P^{[k]}}}{d^{[k]}} I^{[k*]}. \tag{2.22}$$

$U^{[k]}$ obtained to minimize $I^{[k*]}$ will also minimize $I_w^{[k*]}$. Since, $I_w = \sum_{k=1}^{k} I_w^{[k*]}$, we

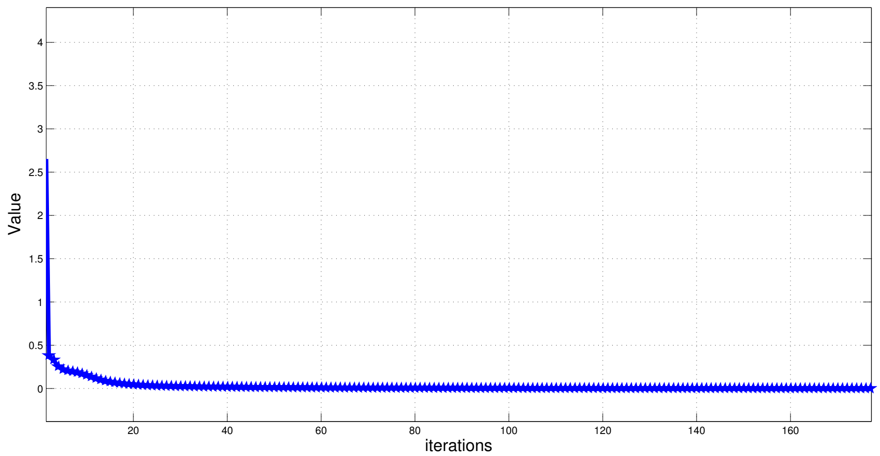

Figure 2.3: Convergence of Algorithm

have

$$\min_{U^{[1]},U^{[2]},...,U^{[K]}} I_w = \sum_{k=1}^{K} \frac{\overleftarrow{P^{[k]}}}{d^{[k]}} [\min_{U^{[k]}} I^{[k*]}]$$

Similarly, WLI associated with transmitter l is

$$I_w^{[l*]} = \sum_{k=1}^{K} \sum_{l=1,j\neq k} \frac{\overleftarrow{P^{[k]}}}{d^{[k]}} \frac{P^{[l]}}{d^{[l]}} Tr(\overleftarrow{U}^{[l]\dagger} \overleftarrow{Q}^{[k]} \overleftarrow{U}^{[k]})$$

Therefore the value of $\overleftarrow{U^{[l}}$ computed to minimize the $\overleftarrow{I^{[l*]}}$ also minimizes $I_w^{[l*]}$. Since $I_w = \sum_{k=1}^{K} I_w^{[j*]}$ and I_w is monotonically reduced for every iteration, convergence of algorithm is guaranteed [2].

2.4.2 Algorithm for subspace optimization-based IA

For given precoders $V^{[l]}, l = 1, 2..., K$, the decoder $U^{[k]}$ should be designed to suppress the interference leakage, and enhance the signal subspace. The objective function for maximizing the signal subspace is

$$max\ \mathcal{F}^{[k]} = Tr(\frac{P^{[k]}}{d^{[k]}} U^{[k]\dagger} H^{[kk]} V^{[k]} V^{[k]\dagger} H^{[kk]\dagger} U^{[k]}) \tag{2.23}$$

such that,

$$U^{[k]\dagger} Q^{[k]} U^{[k]} = I_d^{[k]},$$

Now, consider the design of the precoders at transmitters given the decoders (interference suppression matrices) $U^{[k]}, k = 1, 2, ..., K$. The interference due to transmitter l at undesired receivers plus noise is

$$Q^{[l]} = \sum_{k=1,l\neq k}^{K} \frac{P^{[l]}}{d^{[l]}} H^{[kl]\dagger} U^{[k]} U^{[k]\dagger} H^{[kl]} + I_M^{[l]} \tag{2.24}$$

The Eq. 2.24 is identical to Eq. 2.16 if we replace $\overleftarrow{V}^{[k]}$ with $U^{[K]}$ and $\overleftarrow{U}^{[k]}$with $V^{[k]}$, and also the corresponding channel matrices. Thus, the precoder objective function is constructed as

$$max\ \mathcal{F}^{[l]} = Tr(\frac{P^{[k]}}{d^{[k]}} V^{[l]\dagger} H^{[ll]\dagger} U^{[l]} U^{[l]\dagger} H^{[ll]\dagger} V^{[l]}) \tag{2.25}$$

In Eq. 2.23, let $A^{[k]} = \frac{P^{[k]}}{d^{[k]}} H^{[kk]} V^{[k]} V^{[k]\dagger} H^{[kk]\dagger}$ and $A^{[l]} = \frac{P^{[k]}}{d^{[k]}} H^{[ll]\dagger} U^{[l]} U^{[l]\dagger} H^{[ll]\dagger}$. Now the objective function becomes

$$max\ \mathcal{F}^{[k]} = Tr(U^{[k]\dagger} A^{[k]} U^{[k]}) \tag{2.26}$$

such that

$$U^{[k]\dagger} Q^{[k]} U^{[k]} = I_d^{[k]},$$

this is equivalent to

$$\max_{U^{[k]\dagger} Q^{[k]} U^{[k]} = I_d^{[k]}} Tr \frac{U^{[k]\dagger} A^{[k]} U^{[k]}}{U^{[k]\dagger} Q^{[k]} U^{[k]}} \tag{2.27}$$

similarly, when the decoder $U^{[k]}$ is obtained, Eq. 2.26 can we written as

$$\max_{V^{[l]\dagger} Q^{[l]} V^{[l]} = I_d^{[l]}} Tr \frac{V^{[l]\dagger} A^{[l]} U^{[l]}}{V^{[l]\dagger} Q^{[l]} V^{[l]}} \tag{2.28}$$

Proposition 1: To maximize the objective function in Eq. 2.27, $U^{[k]}$ has column with eigen vectors corresponding to the $d^{[k]}$ maximum eigen values of $(Q^{[k]})^{-1} A^{[k]}$ [2]. Similarly, to maximize the objective function in Eq. 2.28, $V^{[l]}$ has column with eigen vectors corresponding to the $d^{[l]}$ maximum eigen values of $(Q^{[l]})^{-1} A^{[l]}$. That is,

$$U^{[k]} = v_{max}^{d_k}((Q^{[k]})^{-1} A^{[k]}) \tag{2.29}$$

$$V^{[l]} = v_{max}^{d_l}((Q^{[l]})^{-1} A^{[l]}) \tag{2.30}$$

Proposition 2: The sum rate of the algorithm is non decreasing along with iterations, and the iter ative coordinated transmission is assured to converge [2]. Also, the Fig. 2.4 shows the convergence of the scheme with iterations.

2.5 Results

Simulations for minimum interference leakage, and maximize SINR algorithms are provided in this section. Fig. 2.5 shows the plot of sum rate and Fig. 2.6 shows the plot of interference leakage for $(4 \times 6, 2)^4$. If we see the sum rate plot, the performance of the subspace optimized-based interference performs slightly better than the iterative interference alignment. This is expected as the former algorithm maximizes the signal

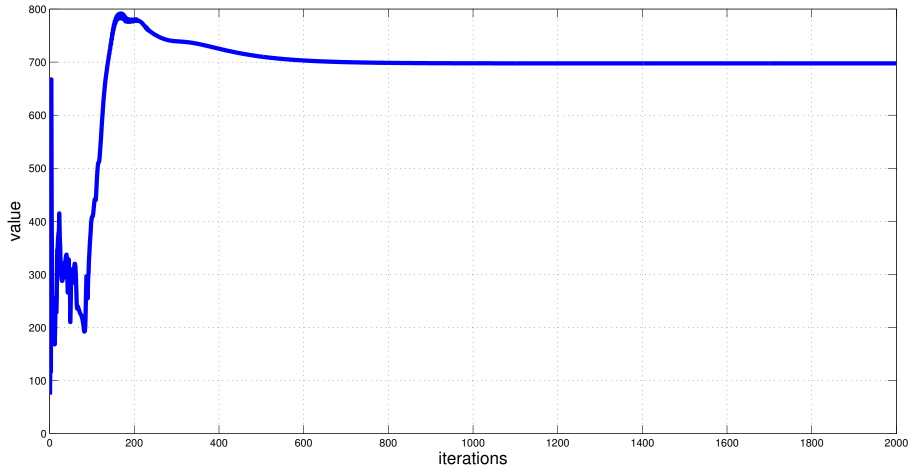

Figure 2.4: Convergence of the Algorithm

to interference plus noise as a whole. Fig. 2.6 shows that as the SNR increases the interference leakage decreases. Also, as the SNR increases both the algorithms achieve the same performance in minimizing the interference leakage.

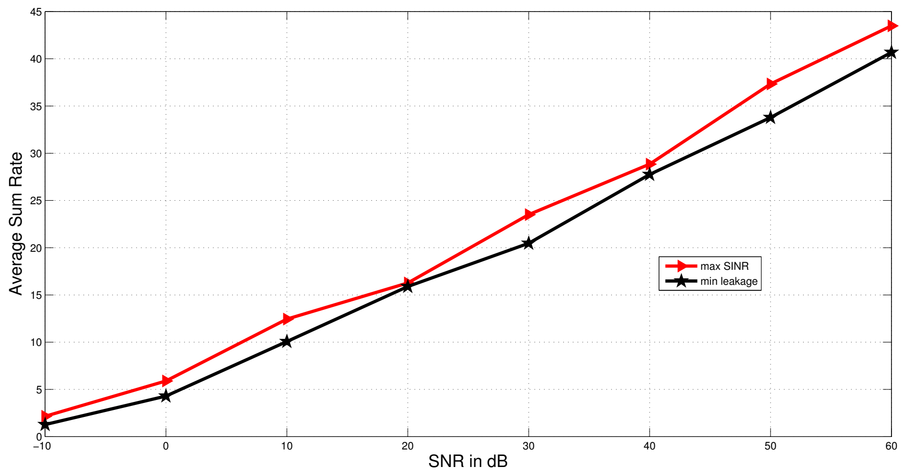

Figure 2.5: Average Sum Rate

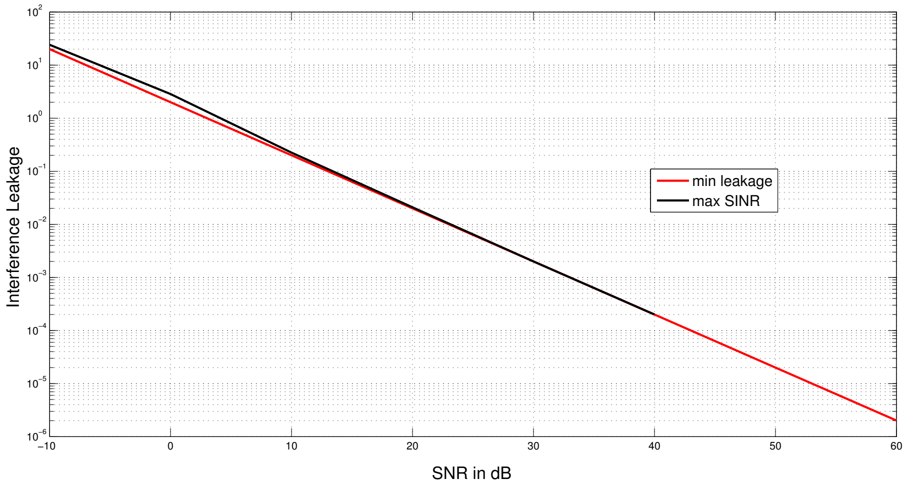

Figure 2.6: Interference Leakage

Part II
Interference Cancelling Block Modulation

CHAPTER 3

Introduction

In this part of thesis, the motivation for interference cancelling block modulation (ICBM) scheme is discussed. Also, an introduction to ICBM and its advantages is presented in this chapter.

3.1 Motivation

ICBM is a block modulation scheme that uses precoding matrices at the transmitters, such that the co-variance matrix of the interference at the receivers is rank deficient. Since, the total distance is equal to the sum of distances along individual dimensions, if atleast one dimension of the signal is free of interference, then co-variance of the interference matrix is guaranteed to be a rank deficient, and the detection of transmit signal/vector is possible. This idea motivates to design precoding matrices at the transmitter.

3.2 Advantages of the proposed scheme:

This section outlines the advantages of the proposed scheme.

- ICBM technique does not require any condition on the fading channel coefficients. It can be used to handle interferences in the finite constellation case, even if all the channel gains in a interference channel are real and equal [3].
- When the receiver is equipped with N receive antennas, up to N-1 non-ICBM interferers can be canceled using conventional optimum combining along with additional interferers that can be handled using the ICBM design. Hence, it is not necessary for all the transmitters to be employing the proposed technique for interference cancellation. This is a very important feature in heterogeneous networks, since it eliminates the need to coordinate the transmissions of all interferers [3].
- Although the optimal design of the precoding matrices depends on the channel gains, fixed matrices can be used to handle the co-channel interference with some

degradation in the performance. Hence, the amount of feedback needed from the user equipment (UE) to the base station is almost non-existent [3].

- Since the interferer's data is not decoded, the receiver complexity is quite less when compared to joint detection [3].

3.3 Scope of the Work

In the rest of thesis, we present ICBM which is a block modulation scheme based on the rank deficient of co-variance matrix of interference at the receiver. Based on the motivation discussed, precoders are designed and assigned to pico BS, attempting to minimize instances where neighboring BSs use the same ICBM matrix.

3.4 Organization of this part of Thesis

The rest of this part of the thesis is organizes as follows. In chapter 4, the system model of ICBM, interference modelling that are discussed in this report are presented. Simulation results comparing the performance of ICBM with reuse 1 are also presented.

CHAPTER 4

Interference Cancelling Block Modulation

In this chapter, system model of ICBM, interference modelling, and simulation results are provided.

4.1 System Model

We consider 3 users equipped with single antenna. Each user has a symbol rate of 2/4. Each user sends two data streams, one is interference free and the other is a common resource i.e., all the 3 users transmit in that resource as shown in Fig. 4.1. Receiver

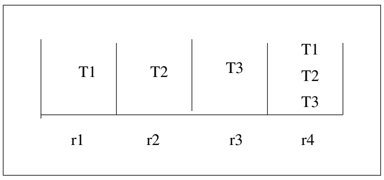

Figure 4.1: Representation of rate-2/4

receives this entire block. The received signal can be expressed as follows

$$y_1 = Q_1 d_1 + \sqrt{\alpha} Q_2 d_2 + \sqrt{\beta} Q_3 d_3 + n_1 \tag{4.1}$$

where, $y_1 \in \mathcal{C}^{N \times 1}$. $Q_j \in \mathcal{R}^{N \times k}$. α denotes the power at which T_2 is received at R_1, and β is the power at which T_3 is received at R_1.

4.2 Modelling interference

Receiver R_1 performs minimum distance detection over d_1 treating $Q_2 d_2$ and $Q_3 d_3$ as noise. Let $\tilde{n} = \sqrt{\alpha} Q_2 d_2 + \sqrt{\beta} Q_3 d_3 + n_1$, since $\tilde{n}_1$ is colored noise with co-variance matrix C_1 given by

$$C_1 = \alpha Q_2 Q_2^{\dagger} + \beta Q_3 Q_3^{\dagger} + \sigma^2 I_N \tag{4.2}$$

where co-variance matrix of interference is given by

$$\tilde{C}_1 = \alpha Q_2 Q_2^{\dagger} + \beta Q_3 Q_3^{\dagger} \tag{4.3}$$

We whiten $\tilde{n}_1$ using Cholesky decomposition. C_1 can be written as $C_1 = L_1 L_1 \dagger$, and using L_1^{-1} we whiten the colored noise. Now Eq. 4.1 can we written as

$$y_1^{'} = L_1^{-1} Q_1 d_1 + n^{'} \tag{4.4}$$

where $y_1^{'} = L_1^{-1} y_1$ and $n^{'} = L_1^{-1} \tilde{n}_1$.

Minimum distance receiver

Now, the minimum distance receiver estimates d_1 given by

$$\hat{d}_1 = arg \min_i \mid\mid (y_1^{'} - L_1^{-1} Q_1 d_1^i) \mid\mid \tag{4.5}$$

$$\hat{d}_1 = arg \min_i (y_1 - Q_1 d_1^i)^{\dagger} C_1^{-1} (y_1 - Q_1 d_1^i) \tag{4.6}$$

Proposition: A necessary condition for the probability of symbol error of the minimum distance receiver of 4.6 to tend to zero as the noise variance $\sigma^2 \to 0$ is that $\tilde{C}_1$ is rank deficient [3].

4.3 Simulation Results

The precoders designed in [3] based on the above proposition are used. We simulated the ICBM for symbol rate-2/4 with 10 physical resource blocks with pilot structure LTE release 10 as shown in Fig. 4.2. Also, we compared the results with reuse-1 communication scheme which employs maximum likelihood (ML) receiver and found that it performs better which is expected as the ML receiver is the optimal receiver. Simulations in Fig 4.3 and 4.4 shows that ICBM performs slightly better than reuse-1 and at low SNR, but reuse-1 outperforms the ICBM scheme at high SNR.

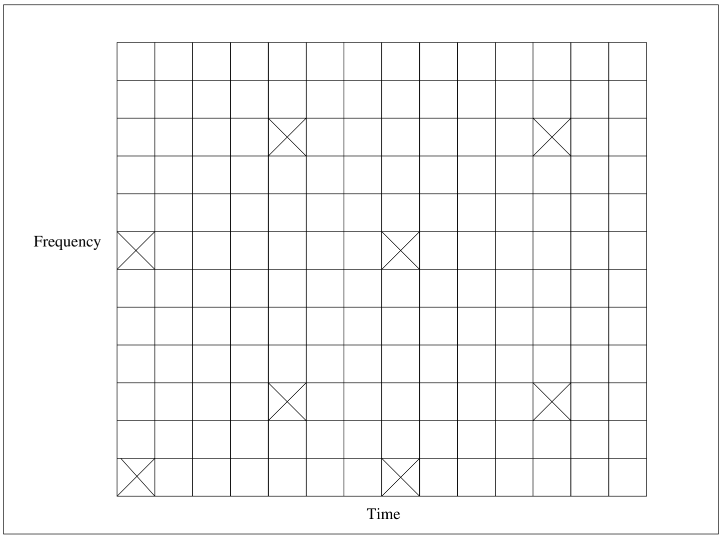

Figure 4.2: Physical resource block with pilot structure

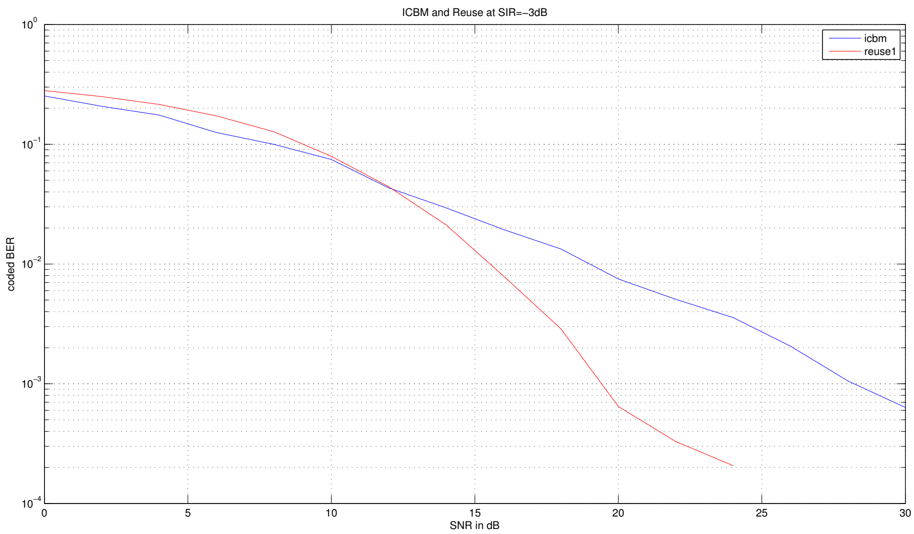

Figure 4.3: BER for SIR=-3dB

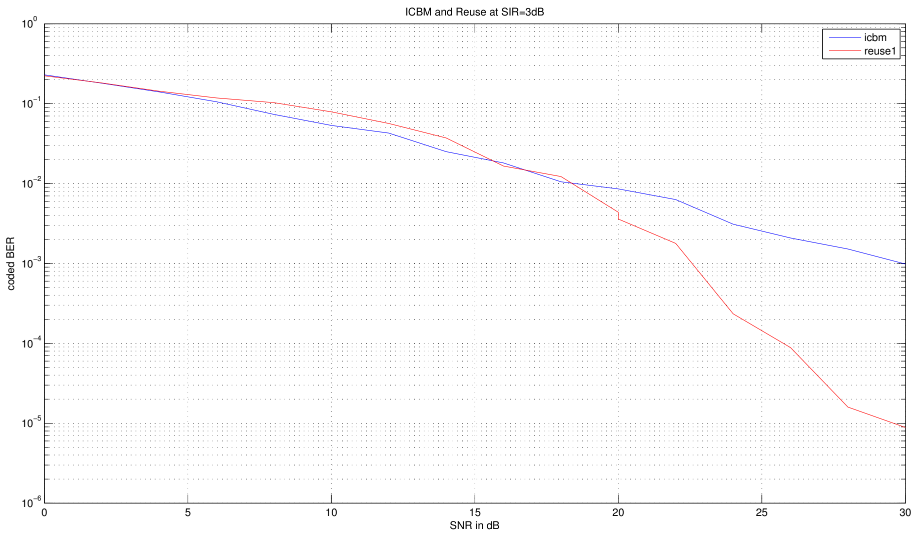

Figure 4.4: BER for SIR=3dB

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