Greedy Algorithm for Stream Selection in a MIMO Interference Channel

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***Abstract*— In this paper, a Greedy stream selection algorithm is proposed for a $M \times N$ K-user Multiple Input Multiple Output Interference Channel (MIMO-IC). The proposed algorithm tries to find the "best stream" allocation by removing streams with low signal-to-interference-plus-noise ratio (SINR) until the system capacity cannot be increased. The algorithm runs with the Minimum Mean Square Error Interference Alignment (MMSE-IA) algorithm and its performance is compared with the exhaustive search by Monte Carlo simulations in two different scenarios. The first scenario is refereed as symmetric attenuation scenario which no path loss is considered among the network nodes. In the second one, by its time, the signal strength is function of the distance, thus more streams are allowed to be transmitted. The results show that the Greedy algorithm outperforms, in both scenarios, any fixed solution and it achieves a good Sum Capacity performance when compared with the best stream allocation (exhaustive search), but with less computational complexity.**

***Keywords*— Interference Alignment, Stream Selection, Sum Capacity.**

I. INTRODUCTION

Nowadays the number of developed mobile applications is growing quickly, as well as the transmission rate required for the proper functioning of these services. Users demand more robust and reliable systems, but bandwidth on a wireless communication system is a scarce and limited resource. Thus, users have to share somehow the transmission resources such as frequency bandwidth, time slots, space dimensions, etc. By sharing them, users may interfere with each others, reducing the system overall performance.

To deal with interference, the transmitters can cooperate with each other by performing a joint transmission. By doing this, the whole system can be seen as a multi-user Multiple-Input Multiple-Output (MIMO) scenario. A well-known algorithm for such case is Block Diagonalization (BD) [1], which is employed in Coordinated Multi-Point (CoMP) communications.

However, because BD is a joint transmission strategy it requires all transmitters to have the data that must be sent to each receiver. The existence of a communication link is not always possible, thus a novel approach that can send data without any transmitter interfering on each other has emerged. The *Interference Alignment* (IA) [2], [3] is a linear preconding technique which is based on the idea that the multiple transmitters in a network try to align the interference at the unintended receivers into a reduced dimensional subspace. The subspace orthogonal to the interference subspace is free from interference and can be used for correctly decoding the desired information.

The degrees of freedom (DoF), by its turn represents how the capacity of a system grows with the log of the signal to noise ratio (SNR) [3]. For an interference channel, it can be seen as the total number of streams that can be sent by the users, thus increasing the DoF of a system implies at higher throughput for the users. In order to maximize the sum rate capacity of the interference channel, some works have exploit how to perform a stream selection strategy [4]–[7]. In [4] the authors used a pricing method for the stream allocation for the max-SINR algorithm. By their turn, in [5], the authors proposed a stream allocation solution and a precoder design based on a procedure that selects the stream with less interference by choosing the beams recursively. In [6] this work was extended by modifying the algorithm presented in [5] for different initialization points. In [7] is extended the work on [6] by proposing a precoder/decoder design for reduce the amount of channel state information (CSI) exchanged by the users pairs.

Different from previous works, we developed an low-complexity algorithm for stream selection in a MIMO interference channel. The Greedy algorithm proposed tries to maximize the achievable rate of the system by exploiting the DoF gain aforementioned. It uses the Minimum Mean Square Error Interference Alignment (MMSE-IA) algorithm for performing the alignment, and at each iteration it removes the stream with lower signal-to-interference-plus-noise ratio (SINR) among all users streams until the sum rate can not grow anymore.

The remainder of this paper is organized as follows. In Section II the problem formulation and the MMSE algorithm are described. In Section III the partially connected scenario is described and the proposed Greedy algorithm is presented. Section IV provides the analysis of the presented algorithm by comparing with fixed solution and exhaustive search by means of Monte Carlo simulations. And, finally, in Section V, some conclusions are drawn.

Throughout this paper, the bold lowercase letter $\mathbf{a}$ represents a vector and the bold uppercase letter $\mathbf{A} \in \mathbb{C}^{i \times j}$ is used to denote a matrix drawn from the $i \times j$ matrix space defined on the complex field. $\mathbf{A}^H$ represents the Hermitan of a matrix $\mathbf{A}$, $\mathbf{A}^{[\star k]}$ is used to denote the k-th column of a matrix $\mathbf{A}$, $\mathbb{R}\{\cdot\}$ corresponds to the real part of a number and, finally, $\mathcal{N}(0, N_0)$ represents a Gaussian distribution with zero mean and variance N_0.

II. SYSTEM MODEL

The system model considered in this paper is shown in Figure 1. The employed channel model is the $M \times N$ K-user MIMO-IC, where K is the number of interfering users

This work is supported by a grant from Ericsson of Brazil - Research Branch under ERBB/UFC.35 Technical Cooperation Contract.

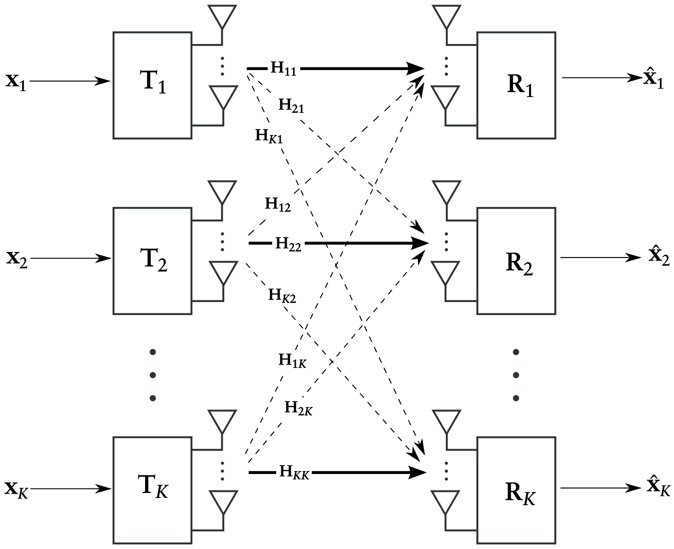

Fig. 1. System Model.

that are sharing the same resource and $\mathbf{H}_{ki} \in \mathbb{C}^{N \times M}$ is the channel matrix between the transmitter i and receiver k . For each user, the transmitter is equipped with M antennas and the receiver is equipped with N antennas.

For a given user k, the received signal $\mathbf{y}_k$ can be written as

$$\begin{aligned} \mathbf{y}_k &= \sum_{i=1}^{K} \mathbf{H}_{ki}\mathbf{V}_i\mathbf{x}_i + \mathbf{n}_k \\ &= \mathbf{H}_{kk}\mathbf{V}_k\mathbf{x}_k + \sum_{\substack{i=1\\ i\neq k}}^{K} \mathbf{H}_{ki}\mathbf{V}_i\mathbf{x}_i + \mathbf{n}_k, \end{aligned} \tag{1}$$

where $\mathbf{x}_k \in \mathbb{C}^{d_k \times 1}$ is the transmit signal of the k-th user, and d_k is the number of degrees of freedom allocated for the user k (number of streams that the user k will transmit to its receiver). $\mathbf{V}_k \in \mathbb{C}^{M \times d_k}$ is the precoder of the k-th transmitter and $\mathbf{n}_k \in \mathbb{C}^{N \times 1}$ is the white Gaussian noise vector with distribution $\mathcal{N}(\mathbf{0},\ N_0\mathbf{I})$ at the k-th receiver.

By applying a receiver filter $\mathbf{U}_k \in \mathbb{C}^{d_k \times N}$ at the received signal, we have

$$\mathbf{U}_k^H\mathbf{y}_k = \mathbf{U}_k^H\mathbf{H}_{kk}\mathbf{V}_k\mathbf{x}_k + \overbrace{\mathbf{U}_k^H\sum_{\substack{i=1\\ i\neq k}}^{K}\mathbf{H}_{ki}\mathbf{V}_i\mathbf{x}_i}^{\varphi} + \mathbf{U}_k^H\mathbf{n}_k. \tag{2}$$

We can note in (2) that φ represents the interference from the unintended users. If the summation term is in the null space of $\mathbf{U_k}$, φ will be equal to zero. Thus, the interference alignment condition can then be mathematically written as

$$\mathbf{U}_k^H\mathbf{H}_{ki}\mathbf{V}_i = \mathbf{0}, \quad \forall k \neq i, \tag{3}$$

$$\mathrm{rank}(\mathbf{U}_k^H\mathbf{H}_{kk}\mathbf{V}_k) = d_k. \tag{4}$$

In the literature, there are many works that have developed algorithms to solve the interference alignment problem such as [2], [8]. Next we will describe the IA Minimum Mean Square Error (IA-MMSE) algorithm.

A pure IA algorithm that solves (3) and (4) is considered suboptimal for low SNR values, since it takes account only the rank of the equivalent channel. The MMSE algorithm seeks a more general objective where IA is just a part of it. It seeks to minimize the Mean Squared Error (MSE) which is the difference between the received and decoded symbol, as described in Eq. (5) below.

$$\mathrm{MSE} = \sum_{k=1}^{K} \mathbb{E}\|\mathbf{U}_k^H\mathbf{y}_k - \mathbf{x}_k\|^2. \tag{5}$$

Replacing (2) in (5), we have

$$\begin{aligned} \mathrm{MSE} = \sum_{k=1}^{K} \mathbb{E}\|\mathbf{U}_k^H(&\mathbf{H}_{kk}\mathbf{V}_k\mathbf{x}_k + \\ &\sum_{i=1, i\neq k}^{K} \mathbf{H}_{ki}\mathbf{V}_i\mathbf{x}_i + \mathbf{n}_k) - \mathbf{x}_k\|^2. \end{aligned} \tag{6}$$

Hence, the MMSE optimization problem is given by

$$\begin{aligned} \min_{\{\mathbf{V}_k\};\{\mathbf{U}_k\}} \sum_{k=1}^{K} &\mathrm{tr}\,(\mathbf{U}_k^H(\sum_{i=1}^{K}\mathbf{H}_{ki}\mathbf{V}_i\mathbf{V}_i^H\mathbf{H}_{ki}^H + N_0\mathbf{I})\mathbf{U}_k) - \\ &2\mathbb{R}\{\mathrm{tr}\,(\mathbf{U}_k^H\mathbf{H}_{kk}\mathbf{V}_k)\} \\ \text{subject to } &\mathrm{tr}(\mathbf{V}_i^H\mathbf{V}_i) \leq P_i; \qquad \forall i \in \{1,\ldots,K\}, \end{aligned} \tag{7}$$

where P_i is the power for each transmitter.

Following the solution for this optimization problem given in [8], the receive filter $\mathbf{U}_k$ can be calculated as

$$\mathbf{U}_k = \left(\sum_{i=1}^{K}\mathbf{H}_{ki}\mathbf{V}_i\mathbf{V}_i^H\mathbf{H}_{ki}^H + N_0\mathbf{I}\right)^{-1}\mathbf{H}_{kk}\mathbf{V}_k, \tag{8}$$

and the precoder $\mathbf{V}_i$ is given by

$$\mathbf{V}_i = \left(\sum_{k=1}^{K}\mathbf{H}_{ki}^H\mathbf{U}_k\mathbf{U}_k^H\mathbf{H}_{ki} + \mu_i\mathbf{I}\right)^{-1}\mathbf{H}_{ii}^H\mathbf{U}_i, \tag{9}$$

where $\mu_i \geqslant 0$ is the Lagrangian Multiplier and it can be found via Newton iterations [9]. This approach is clearly an iterative procedure, thus, in practice, the transmitters first initialize their precoders considering the constraint in (7), then they use (8) and (9) to calculate the precoders and receiver filters until convergence.

III. GREEDY ALGORITHM FOR STREAM SELECTION

As aforementioned in Section I, there are many efforts for increasing the rate of the users. In a MIMO scenario, we can take advantage of the multiple antennas and transmit multiple streams as many as the number of antennas available. However, in a interference scenario, transmitting more streams means to increase the level of interference in the whole system which can lead to a decreasing of the total throughput instead of get more data rate if the interference caused is too high.

The choice, then, is to set a fixed stream allocation that leads to a feasible solution or try to find the best stream allocation by performing an exhaustive search by trying all the possibilities and choose the best one. In the first strategy, even if we find the best number of streams that can be transmitted by checking the feasibility conditions of the system, it does not take account the time changes of the channel, thus this leads to a perform losses when the channel varies along the time. In a scenario with many transmitter/receiver pairs, find the best stream allocation by performing an exhaustive search is not recommended, because the high number of possibilities of choice. In this paper, therefore, we present an algorithm with low complexity that can find a good stream allocation for the scenario described at Figure 1 which outperforms the fixed strategy solution and approximates to the best allocation one.

In order to find a good "stream allocation" we have developed a Greedy Algorithm, whose main idea is to remove streams based on the post-processing SINR value. In other words, we compare all streams of all users, remove the worst one, and then repeat the process until the Sum Capacity of the system is no longer increased by this process. Each time a stream is removed, the previous IA solution is used as a starting point and a new IA solution is found for the new stream configuration.

The algorithm is initialized by setting the number of streams for each user to the maximum allowed value[1].

After running the IA algorithm for the first time, we will have the set of precoders and receiving filter and thus we will be able to compute the post-processing SINR. The SINR for the ℓ-th stream of the k-th user is given by:

$$\mathrm{SINR}_{k\ell} = \frac{\mathbf{U}_k^{[\star\ell]H}\mathbf{H}_{kk}\mathbf{V}_k^{[\star\ell]}\mathbf{V}_k^{[\star\ell]H}\mathbf{H}_{kk}^H\mathbf{U}_k^{[\star\ell]}}{\mathbf{U}_k^{[\star\ell]H}\mathbf{B}_{k\ell}\mathbf{U}_k^{[\star\ell]}}, \tag{10}$$

where $\mathbf{B}_{k\ell}$ is the interference-plus-noise covariance matrix, which is given by

$$\mathbf{B}_{k\ell} = \sum_{i=1}^{K}\sum_{d=1}^{d_i}\Big(\mathbf{H}_{ki}\mathbf{V}_i^{[\star d]}\mathbf{V}_i^{[\star d]H}\mathbf{H}_{ki}^H - \mathbf{H}_{kk}\mathbf{V}_k^{[\star\ell]}\mathbf{V}_k^{[\star\ell]H}\mathbf{H}_{kk}^H + \sigma_n^2\mathbf{I}_{N_k}\Big). \tag{11}$$

After calculating the post-processing SINR of all streams of all users we can calculate the Sum Capacity of the whole system. The stream with the lowest SINR is then removed and the corresponding precoder is updated by removing the column related with the removed stream.

These resulting precoders are used as initialization for the next run of the IA algorithm, which will likely converge faster than the previous run. This stream reduction continues until each user has only one stream left or the Sum Capacity of the system does not improve after the removal of the lowest SINR stream, in which case the solution before the last stream removal is used. The Greedy algorithm is summarized in Algorithm 1.

IV. NUMERICAL RESULTS

In this section we present simulation results to illustrate the performance of the proposed Greedy Algorithm.

Algorithm 1 Greedy Algorithm for Stream Selection.

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1) Initialize (with random precoders) for the maximum number of streams equal to $\min(M-1, N-1)$ for each user;
2) Run the IA algorithm;
3) Store for each user: the number of streams, SINR for each stream (Eq. (10)), precoders (Eq. (9)), receiver filters (Eq. (8)), and the Sum Capacity of the system;
4) Remove the user stream with lower SINR
     • If the user has only one stream, remove the lowest SINR among the remaining users. This is done so each user has, at least, one stream to transmit its data;
     • If all the users have only one stream, end the algorithm;
     • Remove the corresponding column of the precoder of the user with the worst stream;
5) Run the IA algorithm (now the initialization is done with the resulting precoders of step 4) and store the new configuration (as in step 3);
   while (New Sum Capacity $>$ Old Sum Capacity)
       Repeat step 4;
       Repeat step 5;
   end
```

For comparison, we include simulation results for different fixed stream allocation as well as the "best stream allocation" result, which is selected by running the IA algorithm for each possible configuration and choosing the one that yields the highest Sum Capacity.

The scenario is composed by $K = 3$ transmitter/receiver pairs[2], as can be seen in Figure 2. Each transmitter is placed at the center of a cell and its corresponding receiver is placed at a random position in the same cell. The numbers between brackets in the plots represent the number of streams for each user, e.g., [1 2 1] represents one stream for user 1, two streams for user 2 and one stream for user 3. The simulation parameters are summarized in Table I.

TABLE I

SIMULATION PARAMETERS.

Parameter	Value
Number of Monte Carlo Simulations	10,000
Cell Radius	1 km
Number of antennas	3 or 5 at each node
User position	randomly placed inside its cell
Modulation	4-PSK
Path Loss Model (in dB with d in km)	$128.1 + 37.6\log_{10}(d)$
Noise Power	$N_0 = -116.4$ dBm
Transmission Power	Adjusted to match SNR at the border of the cell

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[1] This value can be at most $\min(M, N)$ streams, but in this paper we will use $\min(M-1, N-1)$ to leave at least one dimension where the interference from the unintended transmitters can be aligned.

[2] Best stream allocation can be found by an exhaustive search here because we are limiting the simulation to only 3 transmitter/receiver pairs.

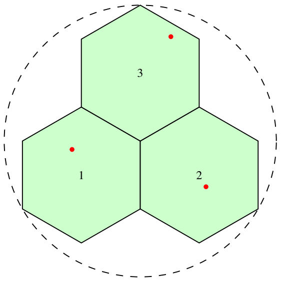

Fig. 2. 3 cells scenario. Each cell has one transmit/receiver pair. The dots represent the users that are randomly placed within the cell. The transmitters are placed in the center of each cell.

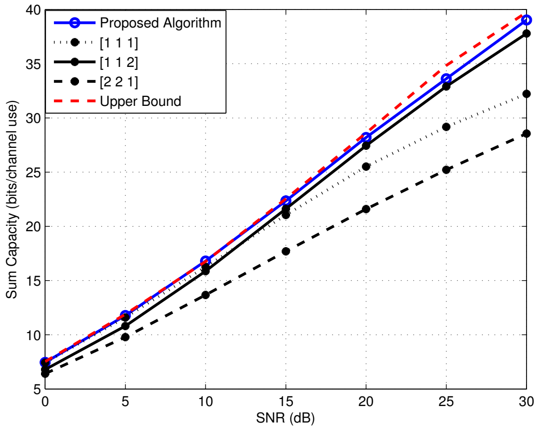

Fig. 3. Sum Capacity versus SNR for the case with no path loss and 3 transmit/receive antennas.

A. No Path Loss Case

Initially we simulate the case where all links, direct and interfering links, have similar path losses [3]. More specifically, we do not include path loss calculation in the simulation and each link is modeled as a random Gaussian matrix with zero mean and an identity covariance matrix. Since all interfering links have similar power with respect to the direct channel this case corresponds to the fully connected interference alignment in the literature and maximum performance is attained (at the high SNR regime) when the total number of streams respects the feasibility conditions addressed in [10], [11].

Figure 3 shows the Sum Capacity versus SNR for the different streams configurations when each node has 3 antennas. We can see that the proposed Greedy Algorithm outperforms the case of best fixed solution [1 1 2][4]. The reason is that the fixed solution is an average of the Sum Capacity over the realizations for each SNR value, whereas the proposed algorithm tries to find the best solution at each channel realization.

Table II shows the percentages for which each stream configuration was chosen by the greedy algorithm.

TABLE II

SELECTION PERCENTAGE FOR EACH CONFIGURATION IN NO PATH LOSS CASE FOR TX = RX = 3.

Streams \ SNR	0 dB	5 dB	10 dB	15 dB	20 dB	25 dB	30 dB
[111]	83,5%	64%	41.6%	20.2%	6.5%	1.7%	0.9%
[112]	4.7%	10.7%	18.4%	26.2%	31.5%	33.6%	33%
[121]	4.7%	11.5%	19.2%	25.8%	30%	32%	32.5%
[211]	5.4%	11.4%	19.1%	27.3%	31.9%	32.6%	33.6%
[221]	0.7%	0.7%	0.4%	0.1%	0.06%	0.02%	0%
[122]	0.7%	0.9%	0.4%	0.2%	0.02%	0.02%	0%
[221]	0.7%	0.7%	0.4%	0.2%	0%	0.01%	0%
[222]	0.2%	0.1%	0.5%	0%	0.02	0.05%	0%

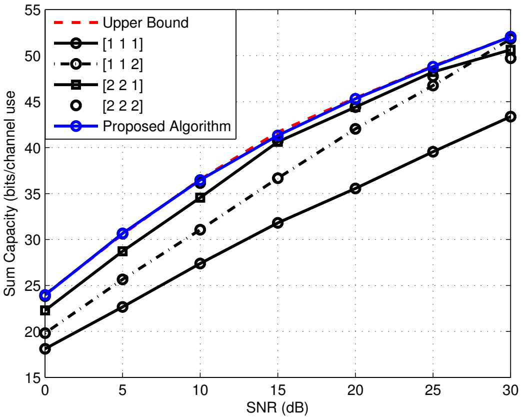

Fig. 4. Sum Capacity versus SNR for path loss case and 3 transmit/receive antennas.

In the low SNR regime noise is the main concern and the proposed algorithm often chooses the [1 1 1] solution as the one with better capacity, since if one user transmits more streams it needs to divide the limited transmit power among the streams. On the other hand, for high SNR regime interference is the main concern and the greedy algorithm avoids any stream allocation which would send more streams than what is possible while keeping IA feasible. The [1 1 1] configuration can be selected in the high SNR regime, but usually the algorithm will prefer to send a total of 4 streams instead of just 3.

B. Path Loss Case

In practice, heterogeneous path loss between the users and base stations induces a scenario between the fully connected interference topology and the *partially connected interference topology* in [12], [13]. The users can take advantage of this configuration by sending more streams, thus improving the system capacity. In order to analyze the performance of the proposed Greedy algorithm in the presence of heterogeneous path loss we simulate cases with 3 and 5 transmit/receive antennas. They are illustrated, respectively, in Figure 4 and Figure 5 where we show the system capacity versus SNR values.

Compared with Figure 3 we see that a configuration with a total of 5 or even 6 streams can work well in the heterogeneous path loss case, while in the previous case with uniform path loss they would perform badly. From the plot, we can see that our proposed algorithm again reaches a performance

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[3] This configuration does not represent a realistic scenario. It corresponds, for instance, to a scenario that all the transmitters are close from each other and all receivers have the same distance to its transmitter.

[4] In this scenario with 3 users and 3 antennas at each node IA is feasible if two users transmit one stream and one user transmit two streams, but no more. On average, performance of [1 1 2], [1 2 1] and [2 1 1] are the same.

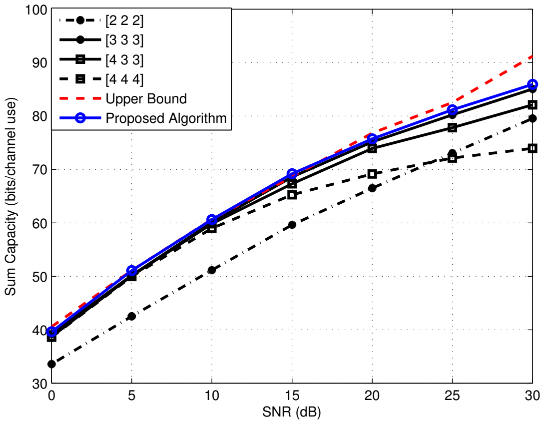

Fig. 5. Sum Capacity versus SNR for path loss case and 5 transmit/receive antennas.

close to the upper bound. Table III shows the percentages for which each stream configuration was chosen by the greedy algorithm and can be used to explain the behavior in Figure 4. Interestingly, the results in Table III seem like the opposite of the results in Table II.

TABLE III

SELECTION PERCENTAGE FOR EACH CONFIGURATION IN PATH LOSS CASE FOR TX = RX = 3.

SNR / Streams	0 dB	5 dB	10 dB	15 dB	20 dB	25 dB	30 dB
[111]	0%	0%	0%	0%	0%	0%	0%
[112]	0.05%	0.05%	0.04%	0.3%	2%	6.8%	11.5%
[121]	0.07%	0.01%	0.03%	0.3%	1.6%	7.3%	16.1%
[211]	0.1%	0.04%	0.03%	0.3%	1.7%	7.8%	16.5%
[122]	2.1%	1.7%	2.3%	5%	8.6%	7.7%	5.6%
[221]	4%	4%	7.2%	14.7%	22.5%	19.8%	12.2%
[221]	2.6%	1.8%	2.5%	5.3%	9%	8.1%	5.5%
[222]	91%	92.4%	87.9%	74.1%	54.6%	42.5%	32.6%

As we have low power and path loss among the interfering links, the interference caused by the unintended transmitters, at a given receiver, is small. Thus, all the users can use the maximum number of allowed streams, two in our simulation here, and still achieve good performance. As the SNR gets higher, the transmission power and the interference, grows but the relative difference in terms of path losses does not change, since it only depends on the distances between the nodes. This behavior can also be seen in Figure 5 where now we have 5 transmit/receive antennas. The Greedy algorithm is a suboptimal approach, then, sometimes, it do not choose a good stream configuration as we can see when the SINR is 30 dB. However, its performance is always better or, at least, equal to any fixed solution. Therefore, the behavior of the algorithm goes towards the behavior in the homogeneous path loss case, which can be considered a kind of a lower bound on the number of streams that can be sent in the non-homogeneous path loss case.

C. *Complexity Analysis*

In order to motivate the use of our Greedy approach we compare the number of iterations needed for the two presented algorithms. The exhaustive search needs to evaluate all the possible stream configurations, then the number of iterations needed to find the best solution is $\mathcal{O}(\min(M,N)^K)$. The proposed Greedy algorithm eliminates some stream configurations during its execution, then, the maximum number of iterations is $\mathcal{O}((\min(M,N)) \times K)$.

V. CONCLUSIONS

The non homogeneous path loss somewhat relaxes how many streams need to actually be aligned for the system to perform well, without a performance floor at the high SNR regime. This allows the transmission of more streams than would normally be possible in a way similar to what is discussed in [12], [13].

The Greedy Algorithm was investigated in order to select the best stream allocation that maximizes the system throughput. By comparing the proposed Greedy Algorithm with an exhaustive search, we illustrated that the greedy algorithm can achieve a satisfactory performance compared with the best solution, but with less computational complexity.

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