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**Pilot Decontamination in Multi-Cell Massive MIMO Systems via Combining Semi-Blind Channel Estimation With Pilot Assignment**

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 **ABSTRACT** In the multi-cell massive multiple-input multiple-output (MIMO) systems, the mitigationof pilot contamination is an important issue in the semi-blind channel estimations. For the pilot decon-tamination schemes, the performance of the semi-blind based estimation approaches is constrained by the ratio of the interference signal power to the target signal power. In order to eliminate pilot contamination effectively, the eigenvalues of the target signals should be separated from those of the interference signals. In this paper, we propose a novel uplink channel estimation for mitigating pilot contamination in time division duplex massive MIMO systems, which combines pilot assignments with semi-blind channel estimation methods. In order to reduce the search complexity for the optimal pilot assignment under the condition of a large number of users per cell, we proposed a sector-based pilot assignment method, including inter-sector pilot assignment and intra-sector pilot optimization. Simulation results verify that the joint pilot allocation and semi-blind channel estimation method is capable of improving the system achievable rates and the normalized mean square error performance.

 **INDEX TERMS** Massive MIMO, pilot decontamination, semi-blind channel estimation, pilot assignment.

**I. INTRODUCTION**

Y employing a large number of service antennas at the Bbase stations (BSs), massive multiple-input multiple-output (MIMO) technique has the capability of increasing throughputs and bringing other advantages, such as small latency, energy saving, and low spectrum overhead [1], [2]. In order to make full use of the benefits of massive MIMO, channel state information (CSI) is a necessity for system optimization. As a result, channel estimation is a hot topic in the research on massive MIMO. Currently, a lot of studies on channel estimation focus on single cell massive MIMO system [3]. Given accurate CSI by reverse-link channel estimation [4], forward-link CSI can be obtained through channel reciprocity in time-division duplex(TDD) massive MIMO systems. In this paper, we focus on a more practical scenario, i.e., multi-cell multi-user (MCMU) massive MIMO

systems. However, due to the reuse of pilot sequences across the neighbouring cells, pilot contamination is a vital issue in the channel estimation of massive MIMO systems. Intra-cell pilot contamination is removed by allocating the orthogonal pilot sequences to the users within the same cell, whereas the non-orthogonal pilot sequences are adopted across the different cells, which bring inter-cell interference (named as pilot contamination) in channel estimation. Due to pi-lot contamination, the performance of a plenty of wireless data services is degraded. For example, pilot contamination caused by an increasing number of smart devices leads to a limited achievable rate and low spectrum efficiency for users, especially at the cell edge [5], [6].

In order to improve the system performance, the mitigation of pilot contamination should be addressed. In the existing literatures, pilot contamination is eliminated through precod-

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ing [7] and power allocation [8] at the BS. It is noted that the literatures [7], [8] are on the focus of pilot-based channel estimation. By leveraging the optimization of pilot assign-ment, pilot contamination can also be reduced substantially. It is known that semi-blind channel estimation is an effective technique in the massive MIMO system due to the low spectrum overhead. Thus, in this paper, we aim at reducing pilot contamination through the combination of semi-blind channel estimation with pilot assignment. In the following, the literatures on the semi-blind channel estimation and pilot assignment are reviewed carefully.

**A. SEMI-BLIND CHANNEL ESTIMATION**

To overcome pilot contamination, a couple of schemes are proposed for the pilot-based approaches and subspace-based approaches, respectively [9]. In [3], a linear pilot method is proposed for channel estimation. Chu sequences with perfect auto-correlation property and corresponding optimal pilot assignment schemes are designed in [10], [11] to minimise the effect of pilot contamination. By using a pilot-based scheme, a maximum a-posteriori (MAP) method extracts the interference eigenvectors together with target signals eigenvectors, and then obtains the estimated channel matrix through combinatorial optimization [12], [13]. Superimposed arrangement methods of the pilots in [14] superimpose the pilot and uplink data in original uplink data slot, and perform power allocation on the pilot and uplink data to obtain a better system capacity. Superimposed arrangement methods of the pilots are further extended to multi-path channels in

1. Besides, a classical greedy pilot assignment is adopted to minimize the total mean squared error (MSE) and the search complexity in [16]–[18]. However, it still has a high computation complexity in the pilot-based schemes.

For the subspace-based schemes, statistics, such as vari-ances and kurtosis [19]–[23], are used to separate the tar-get signals from the noise and interferences. Therefore, the subspace-based approaches are interpreted as the semi-blind methods in general, which can be divide into two cate-gories: singular value decomposition (SVD)-based method and eigenvalue decomposition (EVD)-based method. By us-ing the eigenvalue distribution of the covariance matrix of the received signals, the SVD-based methods mainly depict the separation characteristics of the eigenvalues of the target signals and interference signals [24]–[27]. In the imple-mentation of the real-world channel estimation, SVD-based methods directly estimate the symmetric signal subspace channel matrix, whereas the EVD-based methods are used to calculate the exact CSI.

By extrapolating the symmetric signal subspace channel matrix, the EVD-based channel estimation methods are de-signed to calculate small-scale fading channel matrix in [28]–

1. In the ideal case of massive MIMO systems, [28] points out that the small scale fading matrix is the product of target signal eigenvectors matrix and diagonal ambiguity matrix. When the number of received antennas tends to infinity in massive MIMO systems, the separation characteristics of

the eigenvalues of the target signals and interference signals depend on three parameters: the number of interfering cells, the ratio of the user numbers in each cell to the coherent symbol length, and the ratio of the received interference power to the desired signal power [33], [34]. For a given wireless system, the number of interfering cells and the ratio of the user numbers in each cell to the coherent symbol length are determined accordingly. Thus, in order to improve the separation performance, the ratio of the received interference power to the desired signal power should be well designed. In [25], [33], a power-controlled hand-off is developed. How-ever, the advantage of inter-cell coordination is ignored in [25], [33], which plays a vital role in the improvement of the separation performance.

In order to utilize the benefits of the pilot-based and semi-blind channel estimation methods, we investigate the combi-nation of pilot assignment and semi-blind channel estimation methods in this paper.

**B. PILOT ASSIGNMENT**

In contrast to the shifting of pilot locations in frames dynam-ically [35], pilot assignment methods make the interfering users far away from the target user with the same pilot sequences in the pilot-based approachs [36]–[39]. Basically, the computation complexity of random pilot assignment (R-PA) is O(1). However, the effect of pilot contamination is se-rious. Exhaustive search pilot assignment (ES-PA) is capable of maximizing the minimum uplink signal-to-interference-plus-noise-ratio (SINR) by traversing all the possible pilot sequences, but ES-PA has an enormous high complexity of O((K!)L), where K is the number of active users per cell and L is the number of cells.

In addition, the edge-weighted interference graph (EWIG) and graph coloring (GC) based pilot assignments are de-signed in [37], [38], which make full use of the average value of the mutual interference across the users and sequentially assign pilot sequences to the users in each cell. In [39], a deep learning-based pilot assignment (DL-PA) utilizes a deep multi-layer perceptron (MLP) to train the neural network by learning the relationship between the pilot assignment schemes of ES-PA and the location patterns of the users. However, in practice, DL-PA requires a large amount of ES-PA train data. Thus, it is difficult to pick out the pilot sequences for maximizing the minimum uplink SINR when the number of users in each cell is greater than 4. In order to enhance the minimum uplink SINR, a pilot assignment is developed in [36], in which the pilot sequence with the highest inter-cell interference is allocated to the user with the best channel quality in the target cell. In semi-blind channel estimation, the minimum uplink SINR is constrained by the largest pilot contamination in the massive MIMO system. If separation condition derived in [25], [33] is satisfied, pilot contamination can be eliminated.

On the other hand, a location aware pilot assignment (LA-PA) is considered in heterogeneous cellular networks (HetNet) in [40]. Macro-users in the same macro-cell are

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assigned to different sectors, which are assigned the pilot sequences with a high priority. Then, small cell users in the central group are assigned pilot sequences by minimizing inter-tier interference. At last, the rest macro-users and small cell users match the residual pilot sequences exhaustively. Therefore, due to a huge number of macro-users and small cell users in HetNet, partitioning is proposed to reduce com-plexity via avoiding the global traversal. Motivated by this concept, sector-based pilot assignment is integrated into the semi-blind channel estimation in the MCMU massive MIMO systems in this paper.

**C. OUR CONTRIBUTIONS**

In this paper, the combination of sector-based smart pilot assignment and semi-blind channel estimation is investigated in the MCMU massive MIMO systems. In order to mitigate the pilot contamination caused by the overlap of target signal eigenvalue bulks and interference signal eigenvalue bulks, we propose a new pilot assignment scheme for semi-blind channel estimation method. The contributions are listed as follows:

Firstly, the semi-blind channel estimation and pilot de-contamination analysis are presented in the MCMU massive MIMO systems. By considering the influence of the location distributions of the users, the relationship between the propagation distance and the ratio of the interference signal power to the target signal power is derived. When the ratio of the interference to the target signal power is larger than a threshold, there will be an overlap between the eigenvalue bulks of the target signal and those of the interference in the EVD-based semi-blind method, which will further lead to pilot contamination.

Secondly, a sector-based pilot assignment is proposed to reduce the interference on the pilot sequences by max-imizing the distance between the users with the same pilot. In the sector-based pilot assignment, each cell is divided into multiple sectors. Then, the implementation of the proposed sector-based scheme includes two steps, i.e., inter-sector pilot assignment is implemented, and then intra-sector pilot assignment is refined by the op-timization method. Compared to the exhaustive search method, the computational complexity of the proposed sector-based scheme is reduced substantially.

Thirdly, the combination of sector-based smart pilot assignment and semi-blind channel estimation is ca-pable of minimizing the upper bound of the ratio of the interference to the desired signal. It is shown by simulations that the combination of the proposed pilot assignment and semi-blind channel estimation method outperforms the existing schemes. To be more specific, the proposed scheme is able to improve average uplink achievable rate and reduce the normalized mean square error (NMSE).

The rest of this paper is organized as follows: in Section II, a MCMU-MIMO system model is introduced. In Section III, a semi-blind channel estimation method and pilot con-tamination elimination analysis are respectively presented. In Section IV, a new sector-based pilot sequences assignment is proposed for inter-sector pilot assignments and intra-sector pilot optimization. In Section V, we give numerical results of NMSE and the average uplink achievable rate per user under the different conditions. Finally, in Section VI, this paper is concluded.

Throughout the paper, we adopt the following notation-

1. lowercase and uppercase boldface letters denote vectors and matrices, respectively; Ef:g is the expectation operator; diagft1; :::; tN g denotes a diagonal matrix with the n-th diag-onal element tn; XT and XH are the transpose and complex-conjugate transpose of matrix X, respectively; CT1 T2 de-notes a complex matrix with T1 rows and T2 columns; IK is a K K identity matrix.
   1. **MCMU-MIMO SYSTEM MODEL**

In this paper, the uplink of a multi-cell massive MIMO scenario is considered, where a hexagonal cell is surrounded by L interfering cells. Hereafter, for the convenience of expressions, the index 0 in the subscript represents the target cell, while the indices for the interfering cells are larger than

1. Each BS equipped with M antennas is located at the center of each hexagonal cell. The radius of each hexagonal cell is RC . In each cell, K single-antenna users are randomly distributed in the BS coverage and are served by their BSs in TDD mode. To make full use of spectrum resource, the frequency reuse factor is 1, i.e., all the cells share the same frequency band. Besides, a block fading channel is assumed, i.e., the channel keeps unchanged during one transmission block but varies from one block to another. The system architecture is illustrated in Fig. 1.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 2500 |  |  |  |  |  |  |  |  |  |  |
| 2000 |  |  |  |  |  |  |  |  |  |  |
| 1500 |  |  |  |  |  |  |  |  |  |  |
| 1000 |  |  |  |  |  |  |  |  |  |  |
| 500 |  |  |  |  |  |  |  |  |  |  |
| 0 |  |  |  |  |  |  |  |  |  |  |
| −500 |  |  |  |  |  |  |  |  |  |  |
| −1000 |  |  |  |  |  |  |  |  |  |  |
| −1500 |  |  |  |  |  |  |  |  |  |  |
| −2000 |  |  |  |  |  |  |  |  |  |  |
| −2500 | −1500 | −1000 | −500 | 0 | 500 | 1000 | 1500 | 2000 | 2500 |  |
| −2000 |  |

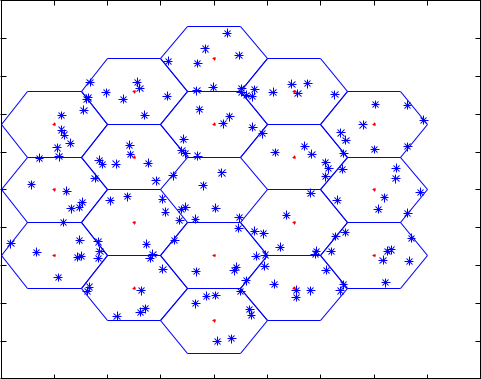


FIGURE 1: An illustration of hexagonal cellular network architecture with L = 18 and K = 8. Red spots represent the BSs; Blue stars represent the users.

It is assumed that C symbols are transmitted during one

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| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| transmission block. In each block, both the pilot signals and | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | where Zli;k; rli;k; are the shadowing fading coefficients | | | | | | | | | | | | | | | | | | | | | | | |  |
| information data are transmitted. Hereafter, unless otherwise | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | between BS l and user k in the i-th cell, the propagation | | | | | | | | | | | | | | | | | | | | | | | |  |
| specified, the superscripts "p" and "d" denote the pilot signals | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | distance between BS l and user k in the i-th cell, and the path | | | | | | | | | | | | | | | | | | | | | | | |  |
| and data signals, respectively. Then, the signals received | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | loss | exponent, | | | respectively. In | | | | | | | | | addition, | | | | 10 log10(Zlik) | | | | |  |  |  |
| at the target BS, including pilot and data signals, can be | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | CN (0; shadow), where shadow is usually considered a non- | | | | | | | | | | | | | | | | | | | | | | | |  |
| expressed as | | | | | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | negative constant. Besides, hli(m; k) denotes the small scale | | | | | | | | | | | | | | | | | | | | | | | |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | L | |  |  |  |  |  |  |  |  |  |  | fading coefficient from the kth user in the ith cell to the | | | | | | | | | | | | | | | | | | | | | | | |  |
|  |  |  | R0 = p | | | | | |  |  |  |  | H00S0 + p | | | | | | | |  |  |  |  | Xi | | H0iSi + Z0; | | | | | | | | | (1) | mth antenna of the lth BS, which follows an independent | | | | | | | | | | | | | | | | | | | | | | | |  |
|  |  |  | pu | | | | pu | |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | =1 | | | |  |  |  |  |  |  |  |  |  |  | identically distribution (i.i.d) and is a circularly-symmetric | | | | | | | | | | | | | | | | | | | | | | | |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | Gaussian random variable with mean zero and variance one, | | | | | | | | | | | | | | | | | | | | | | | |  |
| where R0 = | | | | | | | [Rp; Rd], Z0 | | | | | | | | | | | | | = | | | [Zp; Zd], Sl = | | | | | | | | | | | | [Sp; Sd], | |  |
| Rp | |  |  |  |  | M Np | | | |  | 0 | |  |  | 0 | matrix of | | | | | | |  |  |  | 0 | 0 | |  | pilot | | | |  | l | l | i.e., hli(m; k) CN (0; 1). | | | | | | | | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  | is | | | | the | |  |  | received | | | | |  | signals | in |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 0 2 C | | | | | |  |  |  |  |  |  |  |  |  |  | C | | M Nd | | | | |  |  | is the matrix of received | | | | | | | | | | | | In wireless communications, the change of the small scale | | | | | | | | | | | | | | | | | | | | | | | |  |
| the desired cell, Yd | | | | | | | | | | | | | | | 2 |  |  | fading coefficient hli(m; k) is much faster than the larger | | | | | | | | | | | | | | | | | | | | | | | |  |
|  |  |  |  |  |  |  |  |  |  |  |  | 0 | | |  |  |  |  |  |  |  |  |  |  | p | | 2 CM Np and | | | | | | |  |
| data symbols | | | | | | | with | | | | | | | Np + Nd | | | | | |  |  |  |  | C, | | Z0 | | | scale fading coefficient li;k. Thus, it is quite challenge to | | | | | | | | | | | | | | | | | | | | | | | |  |
| Z0d 2 CM Nd are the matrices of the additive white noise | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | estimate the information of small scale fading matrix, which | | | | | | | | | | | | | | | | | | | | | | | |  |
| on the received pilot and data signals, respectively, whose | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | is also the focus of the existing literatures on this topic. In | | | | | | | | | | | | | | | | | | | | | | | |  |
| elements following the complex Gaussian distribution with | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
| the following, we focus on the channel estimation by using | | | | | | | | | | | | | | | | | | | | | | | |  |
| zero mean and unit variance, i.e., CN (0; 1), Sld 2 CK Nd is | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
| the semi-blind channel estimation. It aims at estimating the | | | | | | | | | | | | | | | | | | | | | | | |  |
| the matrix of the transmitted data of K users in the lth cell for | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | small-scale channel Gli based on the received signals R0 and | | | | | | | | | | | | | | | | | | | | | | | |  |
|  |  |  |  |  |  |  | p | | | | 2 CK Np is the matrix of the transmitted | | | | | | | | | | | | | | | | | | | | | | | | | |  |
| l = 0; 1; :::; L, Sl | | | | | | | | | |  | the assigned pilot sequences. | | | | | | | | | | | | |  |  |  |  |  |  |  |  |  |  |  |  |
| pilot sequences of K users in the lth cell, pu is the average | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| transmit power allocated to each user, and Hli is the M K | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | **III. ANALYSIS OF SEMI-BLIND CHANNEL ESTIMATION** | | | | | | | | | | | | | | | | | | | | | | |  |  |
| channel matrix between the lth BS and the K users located | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | **A. SEMI-BLIND CHANNEL ESTIMATION METHODS** | | | | | | | | | | | | | | | | | | | |  |  |  |  |  |
| in the ith cell. | | | | | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | In semi-blind channel estimation, the EVD-based channel | | | | | | | | | | | | | | | | | | | | | | | |  |
|  | The pilot sequences Sp can be further expressed as | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | l |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | estimation method is adopted in massive MIMO systems, | | | | | | | | | | | | | | | | | | | | | | | |  |
|  |  |  | Slp = | | | |  |  |  |  |  |  |  | [sl1; sl2; :::; slK ]T | | | | | | | | | | | | |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  | Np | | | | | | = |  |  | Np ; | | | | | |  | which requires the pilot sequences and the covariance matrix | | | | | | | | | | | | | | | | | | | | | | | |  |
| where = [qp; q | | | | | | | | | | | |  |  | ; :::; q | | |  |  | ]T | | |  |  |  |  |  | N | | | is the matrix of | | | | | | | of the received signals. In this section, the EVD-based semi- | | | | | | | | | | | | | | | | | | | | | | | |  |
|  |  |  |  | 2 |  |  | C | Np | | pp | | blind channel estimation includes two steps: 1) the small | | | | | | | | | | | | | | | | | | | | | | | |  |
|  |  |  |  |  |  |  | 1 |  |  |  |  | 2 | |  |  |  | Np | |  |  |  |  |  |  | H | = INp , and 2 | | | | | | | | |  |
| the total pilot sequence sets with | | | | | | | | | | | | | | | | | | | | | | | | | | | | scale fading matrix is estimated by using pilot information; 2) | | | | | | | | | | | | | | | | | | | | | | | |  |
| f0; 1gK Np is the pilot assignment permutation matrix with | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | the pilot based estimation small scale fading matrix is refined | | | | | | | | | | | | | | | | | | | | | | | |  |
| K Np. To be more specific, if the i-th pilot qi is assigned | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | by the covariance matrix of the received data signals. The | | | | | | | | | | | | | | | | | | | | | | | |  |
| to the k-th user in the cell, the (k; i)-th element of is 1, | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | detailed processes are implemented as follows. | | | | | | | | | | | | | | | | | |  |  |  |  |  |  |  |
| and the rest elements in the k-th row of are set to be 0. In | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |  |  |  |  |  |  |
| Based on the pilot assignment information and the received | | | | | | | | | | | | | | | | | | | | | | | |  |
| order to improve the performance of channel estimation, we | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
| pilot signals, the estimated small scale fading channel matrix | | | | | | | | | | | | | | | | | | | | | | | |  |
| will investigate how to assign the pilot sequences in Section | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
| ^ p | is calculated as | | | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  | | | | | | | | | | | | | | | | | |  |
| IV. | | H | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  | | | | | | | | | | | | | | | | | |  |
|  | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | |  | | | | | | | | | | | |  |
|  | The channel matrices are characterized by the large scale | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |  |  |  |  | ^ p |  |  |  |  |  |  | p | H |  |  |  |  |  |  | (3) | |  |
| fading matrices and small scale fading matrices, where large | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |  |  |  |  | G | = |  |  |  |  |  |  | Y0 | | : | |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  | Np | |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| scale fading coefficients consists of path loss and shadow | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | The estimated | | | | | covariance matrix of the received data sig- | | | | | | | | | | | | | | | | | | |  |
| fading. The channel matrix between BS l | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | and the users in | | | | | | |  |  | p | | | | | |  |  |  |  |  |  |  |  |  |  |  |  |
| nals can be expressed as | | | | | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| the i-th cell can be expressed as | | | | | | | | | | | | | | | | | | | | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 | |  |  |  |  |  |  |  |  |  |  |  |  |  |
| ^ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | d | | | d H | | | | | | | (4) | |  |
|  | | ( | |  | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | Ry = | |  |  | | | | Y0 | | [Y0 ] | | : |  | | | | |  |
|  | |  | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  | | | | |  | | | | |  |
|  |  | Hli = Gli | | | | | | | | | |  | Dli; | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | Nd | | | | |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  | Dli = diag | | | | | | | | | | |  |  | | |  |  |  |  | | |  |  | |  |  | | |  |  |  | | (2) | Then, the EVD of R^y is carried out as follows: | | | | | | | | | | | | | | | | | | |  |  |  |  |  |  |
|  |  |  | li;1; | | | |  |  | li;2; :::; | | | | | |  | li;K | | | g | | ; | |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  | f |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | ^ |  | ^ | ^ |  | ^ |  |  |  |  |  | S | | ;I;N | | | | ^ | ^ | ^ | ] | H | | ; |  |
|  |  | H | | |  |  |  |  |  | small scale fading matrix with the (m; k)- | | | | | | | | | | | | | | | | | | | | | | | | | | | Ry = [VS; VI ; VN ]diag | | | | | | | | |  |  | [VS; VI; VN | | |  |  |  |
| where | | li is the | | | | |  |  |  |  |  |  |  |  |  | f | |  |  |  |  |  | g |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  | p | |  |  |  | p | | |  |  |  |  |  | p | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | (5) | |  |
| th element hli(m; k), and the diagonal matrix Dli represents | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| the large scale fading matrix with the k-th diagonal element | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | where | | S | 2 |  | CKK; I | | | | | | | | 2 |  | CLK LK and N | | | | | |  |  | 2 |  |
|  | li;k | | , which is constant in C symbol intervals and inde- | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |  |  |  |  |
| pendent of the receiving antenna index. Accordingly, for the | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | C(M( | | L+1) K) (M( | | | | L+1) K) | | | | | | | are the eigenvalue matrices | | | | | | | | | | |  |
| corresponding | | | | to the | | desired | | | | | | | signals, | | | pilot contamination | | | | | | | |  |
| p | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| channel matrix Gli, the element in mth row and kth column | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | caused | | by | the |  | interfering | | | | |  | cells, | | | | and | additive | | | noise, | |  | re- | |  |
| [Gli]m;k | | | |  | = gli(m; k) is the channel coefficient between the | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |  |  |  |
|  | spectively, | | | V^S |  | 2 CM K;V^I | | | | | | | | | 2 CM LK, | | | | and V^N | | | |  | 2 |  |
| m-th antenna of the lth BS and the kth user in the ith cell | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |  |  |
| with gli(m; k) = hli(m; k) | | | | | | | | | | | | | | | | | | | p |  | | | | | . The expression of large | | | | | | | | | | | | CM (M(L+1) K ) are the eigenvector matrices associated | | | | | | | | | | | | | | | | | | | | | | | |  |
| lik | | | | |  |
| scale fading coefficient is given as | | | | | | | | | | | | | | | | | | | | | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  | with S; I , and N , respectively, and the eigenvectors in | | | | | | | | | | | | | | | | | | | | | | | |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  | ^ | associated with the largest | | | | | | | | | | | | K eigenvalues are extracted | | | | | | | | | | |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  | li;k = Zli;k=rli;k; | | | | | | | | | | | | | |  |  |  |  |  |  |  |  |  | VS |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | as the estimated signal subspace matrix. | | | | | | | | | | | | | | | |  |  |  |  |  |  |  |  |  |
| 4 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | VOLUME 4, 2016 | | | | | |  |

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At last, the channel estimation formula can be further derived as

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| ^ | ^ ^ H ^ p | : | (6) |  |
| G00 | = VSVS G |  |

^

where G00 is the estimated small scale fading matrix in

the center cell. The channel estimation in other cells can

be obtained in the same way. In (6), ^ H is leveraged to

VS

eliminate pilot contamination and partial noise from ^ p,

G

^

and VS aims to extrapolate the symmetric signal subspace

channel matrix into the estimated small scale fading matrix ^

G00.

**B. PILOT CONTAMINATION ELIMINATION ANALYSIS**

Due to the reuse of pilot sequences in the neighbouring cells, pilot contamination is caused in the multi-cell massive MIMO scenario. It is shown that the influence of pilot con-tamination is dependent on the interference signal strengthes stemming from the neighbouring cells. It is known that the interference power levels are related to the distribution of interfering users.

In this subsection, we discuss two metrics: 1) the relation-ship between = PI and KC ; 2) the relationship between PI and the propagation distance, where I is the interference power caused by the users in the adjacent cells, P is the desired signal power for user in the target cell, = PI is defined as the ratio of the interference power to the received desired signal power, and KC is defined as the ratio of user numbers per cell to the coherent symbol length.

1) Relationship Between = PI and KC

In [25], the influence of the location distributions of the users in the target cell and the interfering users in the neighbouring cells is not considered. In this case, the ratios of the average received interference power to the average received signal power for all the target users in the desired cell are the same. For massive MIMO system, it has been shown in [25] that the relationship between = PI and KC should satisfy the following constraint, i.e.,

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| K | | (1 ) | 2 |  | 2 | +3(L+1) +12(1+ ) | p |  |  |  |  |
|  |  |  |  |
|  |  |  | (L | | 3L ) | | | : (7) |  |
| C | (L 21)(L | | | 2+6(L1) 1)+(9L 22 | | L+9) 2 | | |  |

Fig. 2 plots the relationship between KC and for L = 4 described in (7). For other L’s, the behaviors of the curves are similar. It is demonstrated that KC is a decreasing function of . For a given wireless communication, KC is determined. In this case, in order to satisfy the condition in (7), the ratio

should be less than a threshold. i.e., should be located in the green area in Fig. 2.

However, when the user locations are taken into consid-eration, it will lead to a different interference power and received signal power ratio for each target user. For user k, the interference power and received signal power ratio

is defined as k, where k = Ik for k 2 f1; :::; Kg.

Pk

In this situation, for any user in the target cell, k should

Follow the condition shown in (7). Then, there must have the relationship given as

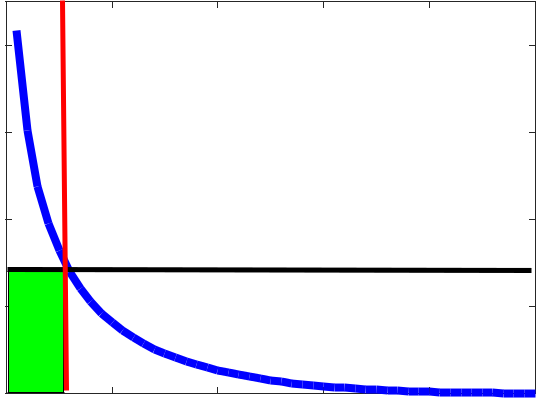
|  |  |
| --- | --- |
| th maxf 1; :::; K g; | (8) |

where th is the threshold to satisfy (7) for a given KC . From

(8), we can also obtain that the minimum uplink signal to

interference ratio (SIR) Pk should be larger than a threshold.

Ik



|  |  |  |
| --- | --- | --- |
|  | 0.4 |  |
|  | 0.3 |  |
| K/C | 0.2 |  |
|  |  |
|  | 0.1 |  |
|  | 0 |  |

0 0.2 0.4 0.6 0.8 1



FIGURE 2: The relationship between KC and with L = 4.

1. Relationship Between PI and the Propagation Distance

Assuming that a user in the i-th interfering cell uses the same pilot sequence qk as a user in the target cell, the slow fading coefficients of the interfering user and the target user are respectively expressed as

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | |  |  |  |  | = | Z00;qk | | | | ; | | |  | = | |  | Z0i;qk | | ; |  |  |  |  | (9) | | |  |
|  |  |  |  |  |  |  | |  |  |  |  |  |  |  |
|  |  |  | 00;qk | | | |  | r00;qk | | | | |  | 0i;qk | |  |  |  | r0i;qk | | | |  |  |  |  |  |  |  |
| Accordingly, the ratio | | | | | | | | | | I | is given by | | | | | | |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  | P | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  | I | | = |  | 0i;qk | | | | = ( | | | Z0i;qk | | )( | | r00;qk | | | ) : | |  |  |  |  | (10) | | |  |
|  |  |  | |  | | |  |  |  | |  | | |  |  |  |  |
|  | P | | | |  |  |  |  |  | Z | 00;qk | |  | r | 0i;qk | | | | |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  | 00;qk | | |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Based | on the | | | | distribution | | | | | | | | of Z0i;qk , it can be | | | | | | | | | | derived | | | | | |  |
| that the | logarithm | | | | | | of the shadowing | | | | | | | | | | | fading ratio | | | | |  | Z0i;qk | | | |  |  |
|  | Z00;q | | | k | |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | Z0i;;qk | | | |  |  |
| follows | a normal | | | | | | distribution, i.e., | | | | | | | | |  |  |  |  |  |  |  | | |  |
|  | 10 log10( | | | | | Z00;qk | | | ) |  |
| CN (0; 2 shadow). | | | | | | | r00;qk | |  | is the ratio of the propagation dis- | | | | | | | | | | | | | | | | | | |  |
| r0i;qk | | |  |

tance between the target user and its serving BS to that between the interfering user using the same pilot sequence

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| and the target BS. Since | | |  | I | | increases exponentially | | | | with | | |  |
| P | | |  |
|  | r00;qk | with the exponent , | is dominant by |  | r00;qk | . Thus, | |  |  |  |
|  | I | |  |  | I |  |  |
|  |  | |  |  |  |
|  | r0i;qk | | P | | |  |  | r0i;qk | |  | P | |  |

can be mitigated through pilots allocation. It has been shown in [35] that the interference stemming from the second-circle cells is easy to satisfy the condition (7), because of the propagation distances between the remaining outer cell users and the target BS are at least twice as the propagation distances between the users in the target cell and the target BS. As a result, in the following, we only focus on the pilot assignment for the first-circle cells in the semi-blind channel estimation.

|  |  |
| --- | --- |
| VOLUME 4, 2016 | 5 |

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**IV. SECTOR-BASED PILOT ASSIGNMENT**

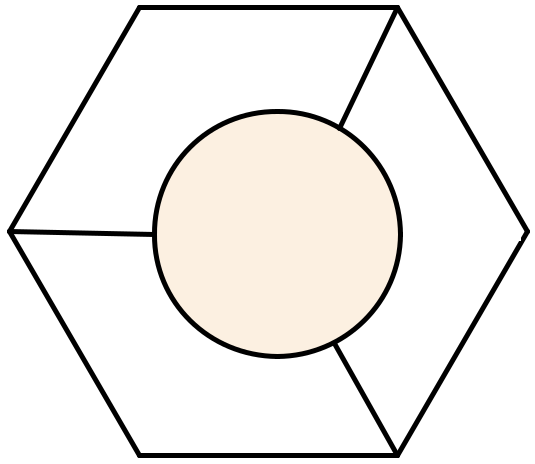
The polar coordinates (r00;qk ; 00;qk ) are used to denote the location information of user k, where r00;qk is the distance between the user and its serving BS, and 00;qk is the angle relative to the horizontal line. It is known that the interference can be reduced by assigning the different pilot sequences to the sector with the least interfering distances. Thus, by using the users location information, the distance between users who share same pilot sequences can be increased.

**A. INTER-SECTOR PILOT ASSIGNMENT**

According to the user location information, the coverage of each cell is divided into K sectors. Then, the pilot sequences are assigned to different sectors by using the criterion ex-pressed as

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 8 |  | for rll;q1 | |  | p | |  |  |  |  |  |  |  |
| q1; | < Rc=p 3 | | | | | |  |  |  |  |
| < |  | for rll;qi | | Rc= |  |  |  |  |  |  |  |  |  |
| lk = | qi; | 3; | | | | |  |  | ; |  |
| : |  | 2(i2) | ll;qi | | 2(i1) | | | | | ; | i = 2; :::; |  |  |
|  | K1 | K1 | | | | | (11) |  |
|  |  |  |  |  |  |  |  |  |  |  |  | K |  |

where lk is the pilot assignment for the kth sector of the lth cell. An illustration of sector division is shown in Fig. 3.



**SECTOR II**

**SECTOR**

cells aiming at minimizing PI . Following this methodology, L cells are assigned sequentially until all the sectors of each cell are assigned the enough pilot sequences.

Next, we discuss the selection of inner sector radius. As mentioned above, the propagation distance of the interfering users located in the second-circle cells are at least twice as the radius of the target users. Considering the equivalence of the problem for inner sector, when the radius of the inner

sector is about 1 times of the cell radius, the overlap of the

~~p~~

3

eigenvalue bulks caused by the interfering users in the inner sector can be neglected.

After the inter-sector pilot assignment is complemented, the intra-sector is implemented in sequence. If the sector has only one user, pilot sequences are assigned to the correspond-ing user in the sector. Then, the pilot sequences assigned to the blank sectors are recycled to the sectors who have multiple users. If there are multiple users in a sector, pilot sequences in the sector are internally assigned so that each user is allocated a pilot sequence. In order to assign the pilot sequence effectively, pilot sequences are optimized in the sector with multiple users by using the smart pilot allocation scheme, which will be presented in the next subsection.

**B. INTRA-SECTOR PILOT ASSIGNMENT BY USING PROPOSED PILOT ASSIGNMENT**

The pilot sequences of the multi-user sectors are randomly

formed in the above subsection. However, this initial as-

signment method is far from the optimal solution. In this

subsection, we focus on the problem: how to optimize the

pilot assignment to each user in the multi-user sector.

**SECTOR I**

**SECTOR III**

**IV**

1) Problem Formulation

We consider the pilot assignments for multiple users located in the same sector. The pilot assignment for the target lth cell is specifically dissected from other cells, and thus pilot assignments for all the cells are independently managed by their own BSs. For all K users in lth cell, their assigned pilot sequences l can be represented as [ l1; l2; :::; lK ],

FIGURE 3: An illustration of the sector division with four sectors in each cell.

1. Discussion on Inner Sector Radius and Inter-Sector Pilot Assignment

Firstly, we consider the interference between the users of the inner sector q1. The distance between the interfering users in the sector with pilot q1 and the target BS is at least twice that of the desired user located in the target cell. Similar to the interfering users of the second-circle cells, the overlap of the eigenvalue bulks caused by the interfering users in the inner sector can be neglected by leveraging the EVD-based semi-blind channel estimation. For the outer sectors, i.e., Sector 2; :::; K, the sectors of two neighbouring cells is paired and the PI s for these two sectors are calculated accordingly. Based on the calculated information about PI s, the pilot sequences are assigned to the sectors of two neighbouring

6

e.g., for K = 8, one assignment scheme may be l = [q1; q7; q3; q6; q5; q2; q8; q4]. In the conventional exhaus-tive search method, the search space is K! for each cell. By using sector-based pilot assignment, the number of the candi-date solutions is Kset = (K1!) (K2!) (K3!) ::: (KS!)

PS

with i=1 Ki = K, where S is the number of sectors having the active users. In fKsg, there maybe exist Ks = 1 for some s. Compared with the conventional exhaustive search method with non-sector, the search space of the proposed sector-based scheme is reduced substantially.

Via pilot assignments, the objective is to maximize the minimum average SIR in each cell. In massive MIMO sys-tems, as the M received base station antennas approaches infinity, the optimization problem in the l-th cell can be formulated as

* )

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  |  |  | 2 |  |  |  |
| P : MAX : min |  |  | ll;k | ; | (12) |  |
| P | | L |  |
| fFlsg 8k | i=0;i6=l li;k2 |  | VOLUME 4, 2016 |  |

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|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| where fFls; s = 1; 2; :::; Ksetg denotes all the candidates of | | | | | | | | | | | | | | It is worth mentioning that the iterations are not required | | | | |  |
| the pilot assignments, and Fls = [ l1; l2; :::; lK ] refers to a | | | | | | | | | | | | | | in the semi-blind channel estimation. Besides, in this paper, | | | | |  |
| particular pilot assignment scheme in lth cell. | | | | | | | | | | | | |  | the pilot assignment scheme is dependent on user location | | | | |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  | information but is independent of semi-blind channel estima- | | | | |  |
| 2) Proposed Pilot Assignment | | | | | | |  |  |  |  |  |  |  | tion. Besides, The convergence speed of the pilot assignment | | | | |  |
| Although the computational complexity of the exhaustive | | | | | | | | | | | | | | algorithm is relatively fast. In the proposed scheme, the | | | | |  |
| search is smaller than that of non-sector, the number of all | | | | | | | | | | | | | | complexity of eigenvalues decomposition of the semi-blind | | | | |  |
| pilot assignments, Kset, is still huge when the number of | | | | | | | | | | | | | | estimation technique is O(M3), where the quantity of M in | | | | |  |
| users in each cell is large. On the other hand, when the | | | | | | | | | | | | | | the actual MIMO systems is within a tolerable range. Thus, | | | | |  |
| greedy method is directly used, it may fall into the trap | | | | | | | | | | | | | | the computational complexity is not very high. | | | | |  |
| of local optimal solution. Therefore, it requires an effective | | | | | | | | | | | | | |  |  |  |  |  |  |
| solution that is capable of reducing the search complexity and | | | | | | | | | | | | | | Algorithm 1 Proposed Sector-based Smart Pilot Assignment | | | |  |  |
| preventing the obtained solution from falling into the local | | | | | | | | | | | | | | Scheme | |  |  |  |  |
| optimal. |  |  |  |  |  |  |  |  |  |  |  |  |  | Input: System parameters: K, L, and th; | | | |  |  |
| For a specific pilot sequence qk, the objective function of | | | | | | | | | | | | | | 1: | Users location information: (rli;k; li;k); | | | |  |
| the problem P can be divided into the signal power of the | | | | | | | | | | | | | | 2: | Large-scale fading coefficients: li;k. | | | |  |
| target lth cell and the interference power stemming from the | | | | | | | | | | | | | | Output: | |  |  |  |  |
| interfering cells, which can be expressed as | | | | | | | | | | | | |  | 3: | Inter-sector pilot assignment: lk. | | | |  |
|  |  |  |  |  |  |  |  |  | L | |  |  |  | 4: | Intra-sector pilot allocation, | |  |  |  |
|  |  |  | 2 |  |  |  | i |  | X6 | |  | 2 | (13) | 5: | Calculate the initial values: l;qk . | | | |  |
|  |  |  |  |  |  |  |  |  | li;qk : |  |  |  |  |  |  |
| qk = ll;qk ; qk = | | | | | | | |  |  |  |  | 6: | while s < itevnum do | |  |  |  |
|  |  |  |  |  |  |  |  | =0;i =l | | | | |  |  |  |  |
|  |  |  |  |  |  |  |  |  | 7: | l = 0, |  |  |  |  |
| Without loss of generality, there exists a pilot assignment | | | | | | | | | | | | | |  |  |  |  |
| 8: | while l L do |  |  |  |  |
| scheme so that f |  | k gs are sorted in descending order. That | | | | | | | | | | | |  |  |  |  |
|  | 9: | Calculate qk ; qk , | |  |  |  |
| is, |  |  |  |  |  |  |  |  |  |  |  |  |  | 10: | Sort qk ; qk , |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | Flq | | = [qf1 ; qf | | | | 2 ; :::; qfK ]; | | | | | | (14) | 11: | Flq = [qfq1 ; qfq2 ; :::; qfqK ], | | | |  |
|  |  |  |  |  | q | q | |  |  |  | q | |  | 12: | Flq = [qf1 ; qf | 2 ; :::; qfK ], | | |  |
| q | |  |  | q 2 | |  | ::: | |  | q | | K : | (15) |  |
| 1 |  | q | q | q | |  |
|  |  | fq |  | fq |  |  |  |  | fq |  | 13: | Optimized pilot assignment lfqi = qfpi . | | | |  |
| Similarly, there also exists a pilot assignment scheme so | | | | | | | | | | | | | | 14: | end while |  |  |  |  |
| that f k gs are sorted in descending order. That is, | | | | | | | | | | | | |  | 15: end while | |  |  |  |  |
|  | 16: Compare the optimized values to obtain the optimal pilot | | | | |  |
|  | Flp | | = [qf1 ; qf2 ; :::; qfK ]; | | | | | | | | | | (16) |  |
|  |  | assignments lk. |  |  |  |  |
|  |  | fp |  |  | p |  | p |  |  |  | p | | (17) |  |  |  |  |  |
|  |  |  | fp |  |  |  | fp | |  |  |  |  |  |  |
| q 1 | | |  | q | 2 |  | ::: |  |  | q |  | K : |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |

To maximize the objective function in (12), the pilot sequence qfp1 with a large pilot contamination should not be assigned to the target user who has a low channel gain, whereas we should assign qfq1 to the user in the sector which has the best channel quality. Therefore, the optimization schemes of pilot assignment can be expressed as

|  |  |
| --- | --- |
| lfqi = qfpi ; fqi Km; i 2 1; 2; ::; K: | (18) |

where Km is the number of the users in the sector with multi-ple users. Since the sectors have already been allocated, only the Km users in the m-th sector participate in optimization, whereas the pilot sequence of the sector with a single user sectors remains to be fixed.

To apply the proposed method to the whole system with L + 1 cells, the above method is used to optimize the pilot assignments of the multi-user sectors for all L + 1 cells in sequence. Because the pilot assignments for the L + 1 cells are coupled, the proposed optimization process should be iterated for many times until the solution converges. Let itevnum denote the maximum number of iteration. The procedures of our proposed pilot assignment method are summarized in Algorithm 1.

**V. NUMERICAL RESULTS**

In this section, we consider a MCMU-MIMO system with L + 1 cells, including one center cell and L interfering cells, where each cell has K users equipped with a single antenna and a BS equipped with M antennas. Pilot sequences within the same cell are orthogonal to each other, and all cells reuse the same set of pilot sequences. The average received signal-to-noise ratio (SNR) for the k-th user in the j-th cell is pu jj;k. The detailed parameters are shown in Table 1.

TABLE 1: Simulation Parameters

|  |  |
| --- | --- |
| Number of interfering cells L | 3, 6 |
| Number of BS antennas M | 32 M 512 |
| Number of users in each cell K | 3K10 |
| Coherent symbol length C | 100; 300; 1000 |
| Radius of each hexagonal cell Rc | 500 m |
| Radius of the center hole Ri | 35 m |
| Path loss exponents | 3:5 |
| Shadowing fading coefficient shadow | 8dB |
| Signal to noise ratio SNR | 25dB |
| Transmitted power per user | Pu = SNR=M. |
|  |  |

|  |  |
| --- | --- |
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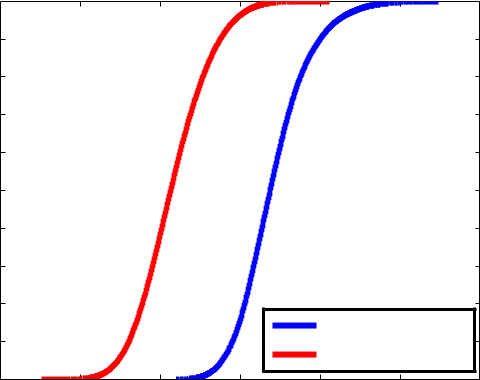


C. Hu et al.: Pilot Decontamination of Combined Semi-blind Channel Estimation and Pilot Assignment in Massive MIMO Systems

1. **THE STATISTICS OF LARGE SCALE FADING COEFFICIENT AND THE THRESHOLD OF** PI

Fig. 4 plots the cumulative distribution function (CDF) of the logarithmic large scale fading coefficients of the signal of interest and the interference links. It is shown that the CDF of the interfering links is located at the left of the desired links. Via the simulation results, it can be obtained that the mean value of large scale fading coefficients of signals of interest is 309.385 and the mean value of large scale fading coefficients of interference link is 0.1925. The worst case is that the large scale fading coefficient of signals of interest is the minimum value, whereas the large scale fading coefficient of interference link achieves the maximum value. In simulations, the minimum value of the large scale fading coefficients of signals of interest is 0.0053, and the maximum value of the large scale fading coefficients of interference link is 323.138. However, when comparing the large scale fading coefficients between the target signals and interference links, it can be observed that the probability of the large scale fading coefficients of interference links is larger than the large scale fading coefficients of target signals is about 7:15%, which inevitably makes the eigenvectors of the desired signals be replaced by the eigenvectors of the interference signals in the semi-blind channel estimation.

|  |  |  |
| --- | --- | --- |
|  | 1 |  |
|  | 0.9 |  |
|  | 0.8 |  |
|  | 0.7 |  |
| CDF | 0.6 |  |
| 0.5 |  |
|  |  |
|  | 0.4 |  |



0.3

0.2

Signals of interest β00k

0.1

Interferences β0ik

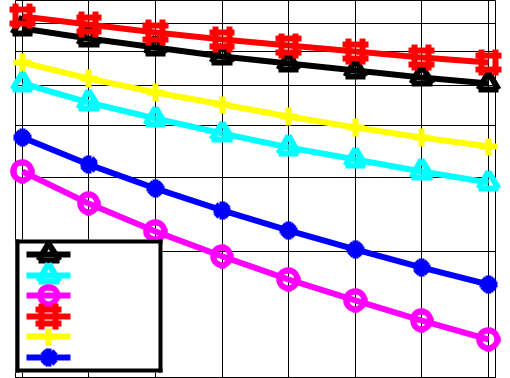
|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| 0 | −10 | −5 | 0 | 5 | 10 | 15 |  |
| −15 |  |

Distribution of logarithmic slow fading coefficients

FIGURE 4: CDF of the logarithmic large scale fading coeffi-

cients with = 3:5 and shadow = 8dB.

such as in the high-speed mobile application scenarios, it can only tolerate a small interference to desired power ratio. Therefore, by using an appropriate allocation method of pilot sequences, an increasing number of the target users meet the constraint condition on PI given in Subsection III-B. This operation will reduce the overlap of eigenvalues, and thus the system capacity will be increased.



|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| I/P |  |  |  |  |  |  |  |  |
|  | L=6,C=1000 | |  |  |  |  |  |  |
|  | L=6,C=300 |  |  |  |  |  |  |  |
|  | L=6,C=100 |  |  |  |  |  |  |  |
|  | L=3,C=1000 | |  |  |  |  |  |  |
|  | L=3,C=300 |  |  |  |  |  |  |  |
| 10−1 | L=3,C=100 |  |  |  |  |  |  |  |
| 4 | 5 | 6 | 7 | 8 | 9 | 10 |  |
| 3 |  |

Number of single−antenna users (K)

FIGURE 5: The threshold of PI to separate the target signal eigenvalue bulks and interference eigenvalue bulks with = 3:5 and shadow = 8dB.

**B. COMPLEXITY ANALYSIS**

Fig. 6 plots the logarithmic computational complexity of the exhaustive search pilot assignment and the proposed pilot assignment. As the number of cells and single antenna users in each cell increases, the complexity of both the exhaustive search pilot assignment and the proposed pilot assignments increases exponentially. It is also shown that the computa-tional complexity of the exhaustive search scheme is always larger than that of the proposed pilot assignment scheme. By using sector division, the maximum received interference power and target signal power ratio PI is reduced. In addition, the search complexity of traversing all feasible solutions is also reduced.

**C. CAPACITY AND NMSE PERFORMANCE**

In addition, according to eq.(7), when the number of the interfering cells L, the number of users K in each cell and the coherent symbol length C are given, the threshold th can be

calculated accordingly. When the maximum value of f Ik g is

Pk

greater than th, the eigenvalue bulks of the target signal will overlap with those of the interference signals, and thus the situation of the eigenvector substitution described above will occur. Fig. 5 shows the threshold of PI in order to separate the target signal and interference eigenvalue bulks with = 3:5 and shadow = 8 dB. It is shown that more interfering cells have a greater effect on the upper bound of PI . Besides, the upper bound of PI is decreased with the number of users in each cell. When the coherent symbol length C is small,

Fig. 7 plots the average uplink achievable rate per user versus the number of BS antennas M. The average uplink achievable rate can be represented as

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  | n |  |  |  |  | o |  |  |  |  |  |  |  |
| CaveUL = 1 | 0 | E | log2 | (1 + SINRaveUL) | | | | |  |  | k=1 SINRl;k ) | | | |  |
| = 1 | 0 | E | log2 | (1 + |  |  | i=1 | l=1 |  |  |  |
|  |  |  |  | n |  | P | | itev | L | P | | K | | (i) | o |  |
|  |  |  |  |  |  | Pitev |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  | | K |  |  |
|  |  |  |  |  |  |  |  |  |  |  | L |  |  |  |  |

(19)

with

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  | ^ (i) | | | 2 |  |  |  |
| SINR(i) | = |  | jjHll;kjj | | |  | ; | (20) |  |
|  |  | | |  |  |
| l;k | ^ | | (i) | 2 |  | 2 |  |  |  |
|  |  |  |  |  |
|  |  | jj Hlm;kjj | |  | + jj N0jj | | |  |  |

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|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| complexity | 40 |  |  |  |  |  |  |  |  |
| 35 |  | L=6,ES−PAS |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |
| 30 |  | L=6,proposed−PAS | |  |  |  |  |  |
|  | L=3,ES−PAS |  |  |  |  |  |  |
| computational |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |
|  |  | L=3,proposed−PAS | |  |  |  |  |  |
| 25 |  |  |  |  |  |  |  |  |
| 20 |  |  |  |  |  |  |  |  |
| 15 |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |
| Logarithmic | 10 |  |  |  |  |  |  |  |  |
| 5 |  |  |  |  |  |  |  |  |
| 0 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |  |
| 3 |  |
|  | Number of single−antenna users (K) | | | | | |  |  |
|  |  |  |  |

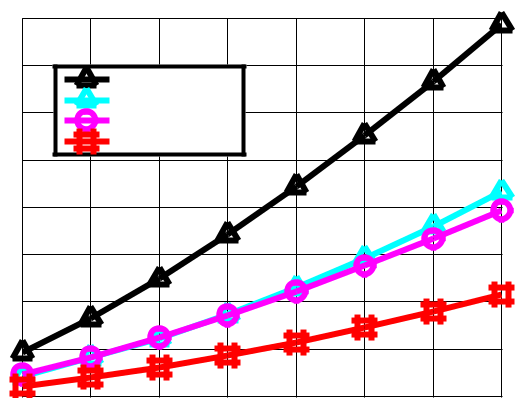


FIGURE 6: The logarithmic computational complexity a-gainst the number of single antenna users K. ES-PAS: exhaustive search pilot assignment scheme; Proposed-PAS: proposed pilot assignment scheme.

where 0 evaluates the uplink pilot spectrum overheads, itev

|  |  |
| --- | --- |
| ^ (i) | ^ (i) |
| is the total iterative number in the simulation, Hll;k | , Hlm;k |

and N0 are the estimated target signals, leaked interference signals, and noise signals in the i-th iteration, respectively. In practice, the parameter should be carefully designed to make a trade-off between pilot overhead and the error of channel estimation. In this paper, the design of pilot overhead is not our focus. Actually, we focus on the pilot assignment in the semi-blind channel estimation. For fairness, in the comparison of the channel capacity for different channel estimation methods, we set the pilot overhead to be a fixed number.

In Fig. 7, it is shown that, in the absence of the eigenvectors substitution described above, the average uplink achievable rates increase with the antenna numbers in the massive MIMO systems for all methods. When the number of in-terference cells L and the number of users K in each cell are considered, the average uplink achievable rate is reduced by 1.5-5 bps/Hz. By using the EVD-based semi-blind chan-nel estimation method, the average uplink achievable rate is increased by 1.88-6.77 bps/Hz because the influence of

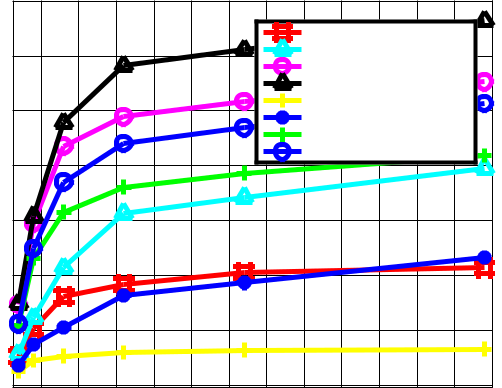
^ (i)

Hlm;k is reduced. Under all different conditions, the av-

erage uplink achievable rate of the proposed pilot assignment scheme is larger than that of the random pilot assignment scheme. It is because the pilot sequences are initialized by sectors to eliminate interference from other cells, and then they are iteratively optimized in our proposed pilot assign-ment scheme. In addition, EVD-based semi-blind methods are used to reduce and eliminate interference and partial noise. Therefore, EVD-based channel estimation method achieves a larger average rate than that of least square (LS) based channel estimation method.

Fig. 8 describes the NMSE peformance versus the number of received antennas M. We consider the pilot-based meth-

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| (bps/Hz) | 16 |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  | (L,K)=(3,4),LS−R−PAS | | | |  |  |  |
| 14 |  |  |  |  |  |  | (L,K)=(3,4),LS−propose−PAS | | | | |  |  |
|  |  |  |  |  |  | (L,K)=(3,4),EVD−R−PAS | | | |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  | (L,K)=(3,4),EVD−propose−PAS | | | | |  |  |
| UE |  |  |  |  |  |  |  |  |  |
| 12 |  |  |  |  |  |  | (L,K)=(6,8),LS−R−PAS | | | |  |  |  |
|  |  |  |  |  |  | (L,K)=(6,8),LS−propose−PAS | | | | |  |  |
| per |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  | (L,K)=(6,8),EVD−R−PAS | | | |  |  |  |
|  |  |  |  |  |  |  | (L,K)=(6,8),EVD−propose−PAS | | | | |  |  |
| capacity |  |  |  |  |  |  |  |  |  |
| 10 |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 8 |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| uplink | 6 |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Average | 4 |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 2 |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | 40 | 80 | 120 | 160 | 200 | 240 | 280 | 320 | 360 | 400 | 440 | 480 | 520 |  |



Number of BS antennas(M)

FIGURE 7: The average uplink achievable rate per user against the number of BS antennas M. LS-R-PAS: least square based with random pilot assignment scheme; LS-propose-PAS: least square based with the proposed pilot assignment scheme; EVD-R-PAS: EVD based with random pilot assignment scheme; EVD-propose-PAS: EVD based with the proposed pilot assignment scheme.

ods and EVD-based semi-blind channel estimation meth-ods with random pilot assignment schemes(R-PAS), pilot assignment schemes in [36] ([30]-PAS), and proposed pilot assignment schemes. Here, NMSE of the least square method can be derived as

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | ^ p | 2 |  |  |
| NMSELS = | EfjjH | H00jj | g |  |
| EfjjH00jj2g | |  |  |
|  |  |  |

Efjj 0jj2g

* EfjjH00jj2g
* k=1 i=1 0i;k + MK

=puNpPKPL

P

* k=1 00;kK

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | K | L | 0i;k + | |  | K |  |  |  |  |
|  | k=1 | =1 |  |  |  |  |  |  |
| = | P | PiK |  | 00;k | puNp | | | : | (21) |  |
|  |  | Pk=1 | |  |  |  |  |  |  |  |

It can be observed that, with the increase of the received antenna numbers M, the NMSEs of LS methods are in-creased accordingly due to the decrease of pu, whereas the NMSEs of EVD-based semi-blind channel estimation meth-ods are gradually decreased. On one hand, the orthogonality of the eigenvectors increases with the increase of the received antenna numbers M. On the other hand, the increase of the distance between the eigenvalue distributions leads to the decrease of the error caused by the decrease of the probability of eigenvalues substitution. The terms f 0i;k g are reshaped by the different pilot assignment schemes, and thus the NMSEs of the two channel estimation methods are reduced at the same time. Furthermore, since the overlap probability of the target signal eigenvalue bulk and interference bulk in the proposed pilot assignment schemes is less than that in smart pilot assignment schemes, the substitution error is reduced.

|  |  |
| --- | --- |
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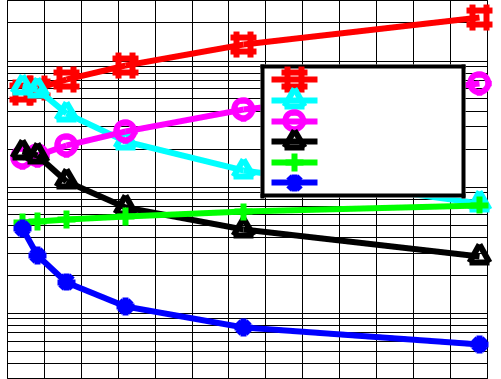
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|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | 10−1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  | LS−R−PAS | |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  | EVD−R−PAS | | |  |  |  |
|  |  |  |  |  |  |  |  |  |  | LS−[30]−PAS | | |  |  |  |
| NMSE |  |  |  |  |  |  |  |  |  | EVD−[30]−PAS | | |  |  |  |
|  |  |  |  |  |  |  |  |  | LS−Proposed−PAS | | | |  |  |
| −2 |  |  |  |  |  |  |  |  | EVD−Proposed−PAS | | | |  |  |
| 10 |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | 10−3 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | 0 | 40 | 80 | 120 | 160 | 200 | 240 | 280 | 320 | 360 | 400 | 440 | 480 | 520 |  |



Number of BS antennas(M)

FIGURE 8: The NMSE versus the number of antennas M with signal perturbation with K = 4 and Nd = 300.

**VI. CONCLUSION**

In this paper, the semi-blind channel estimation in MCMU massive MIMO system is investigated. Considering the ef-fects of the different large-scale fading coefficients for each user, the relationship between the ratio of the interference power to the received desired signal power and the propaga-tion distance is analyzed. Based on the derived relationship, we propose a new joint signal estimation scheme in order to eliminate pilot contamination. In the proposed method, the sector-based pilot assignment scheme is integrated into EVD-based semi-blind method. Simulation experiments show that the combination of proposed pilot assignment with EVD-based semi-blind channel estimation method can reduce the overlap probability. As a result, by using the proposed scheme, the average uplink achievable rate is increased, and the system NMSE is reduced. Besides, the system perfor-mance of our proposed scheme is superior to that of other benchmark schemes.

Fig. 9 shows the overlap probability of the target signal eigenvalue bulks and interference signal eigenvalue bulks. It can be seen that in the case of poor channel conditions, it takes several iterations in the optimization of pilot sequences to reduce the overlap probability of the target signal eigenval-ue bulks and interference bulks. When the number of users

* is large, the proposed pilot assignment schemes make the overlap probability of the target signal eigenvalue bulk and interference bulk become smaller after multiple iterations. In sector-based pilot sequence assignment, the initial value of proposed pilot assignment schemes is small and avoids the obtained solution is far from the optimal value. By the way, when the number of users K in each cell is 3, the overfitting will lead to a limited system performance improvement.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| eigenvalues |  |  |  | K=3,[30]−PAS |  |  |
|  |  |  | K=4,[30]−PAS |  |  |
|  |  |  | K=8,[30]−PAS |  |  |
| 10−1 |  |  | K=3,proposed−PAS |  |  |
|  |  |  | K=4,proposed−PAS |  |  |
| of S&I |  |  |  |  |  |
|  |  |  | K=8,proposed−PAS |  |  |
|  |  |  |  |  |  |
| Probability | 10−2 |  |  |  |  |  |
|  |  |  |  |  |  |
| Overlap | 1 | 3 | 10 | 30 | 100 |  |
|  |  | Number of Iterations | |  |  |
|  |  |  |  |  |

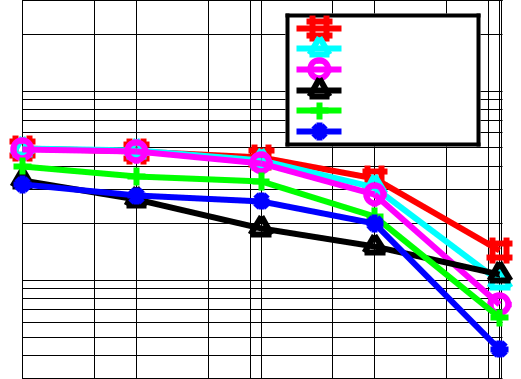


FIGURE 9: Overlap probability of the target signal eigenval-ue bulks and interference signal eigenvalue bulks with L = 7 and Nd = 1000.

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