Low Complexity Antenna Selection Algorithms for Downlink Distributed MIMO Systems

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Abstract—Distributed Multiple Input Multiple Output system (D-MIMO) becomes an attractive topic for increasing system capacity more efficiently. In this paper, we propose a novel two-step antenna selection algorithm for downlink D-MIMO systems. First, the distributed antenna cluster is selected based on maximum path fading, and then the antennas in the selected antenna cluster are chosen utilizing the permutation and QR decomposition (IC-PQRD) method for V-BLAST systems with Ordered Successive Interference Cancellation detection (OSIC). The analysis and simulation results show that the proposed algorithm could greatly enhance the average channel capacity of the downlink distributed antenna systems. Furthermore, in the edge region of a cell, both the system capacity and symbol error probability (SER) are significantly improved due to the antenna cluster selection process. For in-cluster antenna selection in the second step, the IC-PQRD algorithm could largely improve the system outage capacity with low computational complexity and low SER.

Index Terms—Distributed Multiple Input Multiple Output (D-MIMO) System, antenna selection, QR decomposition, ordered successive interference cancellation (OSIC), channel capacity

I. INTRODUCTION

In recent years, conventional multiple input multiple output (MIMO) techniques are regarded as one of the most highlighted wireless transmission schemes for its high spectral efficiency and insensitivity to multi-path fading, and the channel capacity of MIMO systems increases linearly with the minimum number of transmit and receive antennas [1, 2]. Recently proposed distributed antenna system (DAS) can promise an excellent link quality and a higher transmit diversity gain, and improve the cell coverage of wireless broadband cellular networks with low complexity [3-6]. Besides, much attention has been drawn on DAS combining with MIMO, which is called distributed MIMO (D-MIMO) system. It can increase system capacity more efficiently and has become a hot research topic.

Among the implications of employing multiple antennas are the considerable increase in the system complexity and the cost of hardware facilities. The D-MIMO systems equip themselves with many antenna clusters at base station (BS), and also lots of antennas at the mobile station (MS). The total antenna number of the whole D-MIMO system is much more than that of the centralized antenna system (CAS). Therefore, antenna subset selection based on the channel state information (CSI) becomes the key factor for the practical application of D-MIMO systems.

The core idea of antenna selection is to use a limited number of analog chains that is adaptively switched to a subset of the available antennas. In [7], the performance and capacity of downlink pico-cellular DAS is analyzed, and two antenna selection schemes based on the space characteristic are proposed. The authors in [8] have proposed an ascending selection algorithm with QR decomposition, which is quite similar to the Gram-Schmidt orthogonalization procedure at high signal-to-noise ratio (SNRs). A promising approach for the antenna subset descending selection was put forward by Gorokhov [9]. It had proposed an approximate optimal antenna subset selection method based on capacity maximization. Both the algorithms, which belong to greedy algorithm, could reduce the computational complexity in comparison of the optimal exhaustive algorithm. As a well-known practical spatial multiplexing architecture, Vertical-Bell Laboratories Layer Space-Time (V-BLAST) with Ordered Successive Interference Cancellation (OSIC) is characterized as high spectral efficiency with low implementation complexity [10]. Some antenna selection methods designed for the system are introduced in [9, 11, 12], including optimal algorithm, incremental selection, norm based scheme, etc. In this paper, we mainly focus on the V-BALST system with OSIC and propose a novel two-step antenna selection scheme which combines the antenna cluster selection based on maximum path fading with in-cluster antenna selection based on permutation and QR decomposition (IC-PQRD). The proposed scheme could improve the system outage capacity with low computation complexity.

The rest of paper is organized as follows. Section II introduces the system model of the D-MIMO systems. Section III presents the transmit antenna selection algorithm including the antenna clusters selection and the in-cluster antenna selection, and its performance and capacity is also analyzed. Numerical results are presented in section IV. Finally, Section V gives the conclusions of this paper.
II. SYSTEM MODEL

The structure of D-MIMO system using antenna selection algorithm is illustrated in Fig. 1. In a D-MIMO system, there are \( N \) BS antenna ports (i.e. clusters) with \( L \) antennas for each, and \( M \) antennas for each MS. Let us denote it to a \((M, N, L)\) D-MIMO system.

It is assumed that the lognormal macroscopic shadow fades of \( N \) antenna clusters are independent with each other, and channel correlation of small scale fading in antenna cluster is also independent. According to this assumption, we can select the transmit antennas step by step. The channel is linear and quasi-static, which has a flat response across the frequency band. The D-MIMO channel matrix \( H \) is given as

\[
H = \left[ \begin{array}{ccc} H_1^x & \cdots & H_N^x \\ \end{array} \right]_{L \times M} 
\]

where \( d^n \) is the distance from the \( n \)th antenna cluster to the MS, and \( H^x(d^n) \) is \( L \times M \) MIMO channel matrix

\[
H^x(d^n) = \left( \begin{array}{c} h_{1,1}^n \\ \vdots \\ h_{N,1}^n \end{array} \right)_{M \times 1}
\]

where \( L \) denotes the large scale path fading from the \( n \)th antenna cluster to the MS, \( \alpha \) is path loss exponent and usually takes 4. \( H^x \) is the MIMO channel matrix regardless of large scale fading

\[
H^x = \left( \begin{array}{cc} h_{1,1}^n & K \\ M & O \\ \end{array} \right)_{M \times M} 
\]

where \( h_{n,j}^x \) denotes the normalized random variable of small scale fading from the \( i \)th antenna in \( n \)th antenna cluster to the \( m \)th antenna of the MS, and is an independent and identically distributed (i.i.d.), complex and zero mean circular-symmetric Gaussian random variable with variance \( \sigma^2_x \).

As shown in Fig. 2, we simplify the \((M, 4, L)\) D-MIMO system with a single user scenario. We assume that the radius of the cell is \( R \), and the BS has 4 antenna cluster uniformly distributed in the cell. The total transmit power of the \( i \)th antenna cluster is \( P_i \) \((i = 1, 2, L, 4)\) and

\[
\sum_{i=1}^{4} P_i = P
\]

where \( P \) is the total transmit power of the base station. If there is no antenna selection, the received signal at the mobile station is given as

\[
Y = H S + Z
\]

where \( H = \left[ H^H H^\dagger H^H H^\dagger \right] \), transmit signal vector \( S = \left[ (S_1 \ldots S_4) (S_1 \ldots S_4) (S_1 \ldots S_4) \right]^T \), \( Z = \left[ z_1 z_2 z_3 z_4 \right]^T \) is additive complex Gaussian noise vector, \( z_n \) denotes the zero mean Gaussian variable received by the \( n \)th antenna of MS, the variance is \( E[z_n^H z_n] = \sigma^2_z \), where \( E[\cdot] \) denotes the statistic-cal expectation.

However, in the practical D-MIMO system, there is spatial correlation between the adjacent antennas in the antenna clusters and in MS. So it is essential to consider the impact of antenna correlation. \( \rho_{i,j} \) is the correlation coefficient of the \( i \)th and \( j \)th antennas in the antenna cluster or MS and is given as

\[
\rho_{i,j} = J_0 \left( \frac{2\pi(i-j)d_{i,j}}{\lambda} \right)
\]

where \( J_0(x) \) is the primar zero-order Bessel function, \( d_{i,j} \) is the antenna distance, and \( \lambda \) is the wave length of the carrier wave. The correlation matrix \( R_m \) of the receiver is

\[
R_m = \left[ \begin{array}{ccc} 1 & \rho_{1,2} & \rho_{1,M} \\ \rho_{2,1} & 1 & \rho_{2,M} \\ \rho_{M,1} & \rho_{M,2} & 1 \end{array} \right]_{M \times M}
\]
The antenna correlation matrix $R_{n,i}$ in the $n$th cluster can be written as

$$R_{n,i} = \begin{bmatrix} 1 & \rho_{1,2} & L & \rho_{2,1} \\ \rho_{1,2} & 1 & \rho_{2,1} & \rho_{3,2} \\ M & M & O & M \\ \rho_{3,2} & \rho_{2,1} & L & 1 \end{bmatrix}_{L \times L}$$

The total transmit correlation matrix $R_{tx}$ is

$$R_{tx} = \begin{bmatrix} R_{tx,1} & 0 & L & 0 \\ 0 & R_{tx,2} & L & 0 \\ M & M & O & M \\ 0 & 0 & L & R_{tx,N} \end{bmatrix}_{NL \times NL}$$

$$= \text{diag}(R_{tx,1}, R_{tx,2}, L, R_{tx,N})$$

The total transmit correlation matrix $R_{tx}$ with the propagation path fading can be modified as

$$R_{tx} = \begin{bmatrix} L_{1}R_{tx,1} & 0 & L & 0 \\ 0 & L_{2}R_{tx,2} & L & 0 \\ M & M & O & M \\ 0 & 0 & L & L_{N}R_{tx,N} \end{bmatrix}_{NL \times NL}$$

$$= \text{diag}(L_{1}R_{tx,1}, L_{2}R_{tx,2}, L, L_{N}R_{tx,N})$$

So the channel matrix of D-MIMO system considering the correlation is

$$H_{f} = R_{tx}^{1/2}HR_{tx}^{1/2}$$

### III. TRANSMIT ANTENNA SELECTION ALGORITHM

We assume that there is no correlation between the antennas of different antenna clusters, but the correlation exists between the antennas in the same antenna cluster. Therefore, a two-step antenna algorithm is reasonable, including antenna cluster selection and in-cluster antenna selection.

#### A. Antenna Cluster Selection

For this $(M, 4, L)$ D-MIMO system, according to the two-step scheme, we first consider the antenna cluster selection. In order to reduce the system complexity, we select one antenna cluster from all the 4 antenna clusters based on the criteria of maximizing the path fading. The $k$th antenna cluster is selected to transmit the signal

$$k = \arg \max_{n \in \{1,2,4\}} \{L_{1}, L_{2}, L_{4}, L_{4}\}$$

In this step, we can regard the D-MIMO system as a multiple input single output (MISO) system. If CSI is well known to the BS, transmit maximal ratio combining can maximize the transmit diversity gain in a MISO channel. Then, the received SNR could be given as

$$\eta = \frac{\|H(d)w\|^{2}}{\sigma_{e}^{2}}$$

where $w$ is the transmit weight vector. From the Cauchy-Schwarz inequality, it holds that

$$\eta \leq \frac{\|H(d)\|^{2}}{\sigma_{e}^{2}}$$

where $\|\|$ denotes the $L^{2}$ vector norm and the equality is satisfied if and only if $w$ is proportional to $H(d)^{H}$. When the weight vector $w$ is $H(d)^{H}/\|H(d)\|$, the corresponding SNR is

$$\eta = \frac{\|H(d)\|^{2}}{\sigma_{e}^{2}} P_{t}$$

We can obtain that the SER is [13]

$$P_{e} \approx E \left[ N_{0}Q \left( \sqrt{\frac{\eta d_{\text{min}}}{2}} \right) \right]$$

where $N_{0}$ and $d_{\text{min}}$ are the average number and minimum distance of nearest neighbors of the signal constellation in a given modulation mode respectively.

As the probability density function (PDF) of $\eta$ is

$$f_{PDF}(\eta) = \sum_{i=1}^{4} \frac{\sigma_{i}^{2}}{L_{i}P_{i}} \exp \left( -\frac{\sigma_{i}^{2} \eta}{L_{i}P_{i}} \right)$$

where

$$\sigma_{i} = \prod_{j=1,\neq i}^{4} \frac{L_{i}P_{j}}{L_{j}P_{i}}$$

The SER can be obtained as [14]

$$P_{e} \approx \int_{0}^{\infty} N_{0}Q \left( \sqrt{\frac{\eta d_{\text{min}}}{2}} \right) f_{PDF}(\eta) d\eta$$

$$= \sum_{i=1}^{4} \frac{\pi_{i} \eta_{i}}{2} \left( 1 - \frac{d_{\text{min}}^{2}L_{i}P_{i}}{\sqrt{d_{\text{min}}^{2}L_{i}P_{i} + 4\sigma_{i}^{2}}} \right)$$

![Figure 2. (M, 4, L) D-MIMO system model](image)
From (18), the SER when the antenna cluster selection is utilized can be obtained as
\[
SER = \frac{N}{2} \left[ 1 - \sqrt{\frac{d^2_{\min} L P_i}{d^2_{\min} L P_i + 4\sigma^2_s}} \right]
\] (19)

The channel capacity when utilizing this method can be expressed as follows
\[
C_i = -\frac{1}{\ln 2} \exp \left( -\sigma_i^2 L_i P_i \right) \text{Ei} \left( -\sigma_i^2 L_i P_i \right)
\] (20)
where \( \text{Ei}(x) = -\int_x^{\infty} \frac{e^{-t}}{t} \, dt \).

If there is no antenna selection, all the 4 antenna clusters are transmitting the signals, then the system SER is obtained as
\[
SER = \sum_{i=1}^{4} \frac{\pi_i N_{L_i}}{2} \left[ 1 - \sqrt{\frac{d^2_{\min} L_i P_i}{d^2_{\min} L_i P_i + 4\sigma^2_s}} \right]
\] (21)

The channel capacity without antenna selection is
\[
C_{\text{na}} = -\frac{1}{\ln 2} \sum_{i=1}^{4} \pi_i \exp \left( -\sigma_i^2 L_i P_i \right) \text{Ei} \left( -\sigma_i^2 L_i P_i \right)
\] (22)

Moreover, considering fairness, the transmit power of each antenna cluster is \( P/4 \) without antenna selection. And the transmit power of the selected antenna cluster is \( P \) when the antenna selection algorithm based on maximum path fading is employed.

### B. In-Cluster Antenna Selection

After the selection of the proper antenna cluster, this \((M,4,4)\) D-MIMO system could be simplified to a \(L \times M\) downlink MIMO system. We should continue to select \( L_i \) antennas from \( L \) in-cluster antennas to transmit signal. This is identical to select \( L_i \) column vectors from \( L \) ones to form a \( M \times L_i \) matrix \( H_{Li} \), and there are \( L_i \binom{L}{L} \) matrices to choose from.

For the conventional MIMO system, some antenna selection algorithms based on maximum outage capacity have been studied in previous literatures, including the optimal algorithm, the additive iterative algorithm (AIA), the norm-based selection algorithm, and so on. Each individual antenna subset contains a worst-performance substream, and the optimal algorithm is to optimize all individual worst-performance substreams within possible antenna subsets. The algorithms above still need some potential improvements since they are constrained to some special cases. For the vertical-hill laboratory layered space time (V-BLAST) system with ordered successive interference cancellation (OSIC), in order to maximize the outage capacity and improve the detection performance, we propose a fast antenna selection suboptimal algorithm, i.e. IC-PQRD.

We assume that the CSI is perfectly known at the receiver but not at the transmitter. \( E_s \) is the average transmit power of each antenna, \( S = [S_1, S_2, \ldots, S_L]^T \), \( Y = [y_1, y_2, \ldots, y_M]^T \), then
\[
Y = \sqrt{E_s} H_s S + Z
\] (23)

The QR decomposition of \( H_s \) is
\[
H_s = Q_s R_s
\] (24)
where \( Q_s \) satisfies \( Q_s^H Q_s = I \), \( R_s \) is an upper triangular matrix, then we can obtain
\[
W = Q_s^H Y = \sqrt{E_s} R_s S + U
\] (25)
where \( U = Q_s^H Z \), \( |(r_k)_i|^2 \) is the modular square of the \( k \)th diagonal element of \( R_s \), then the \( k \)th substream \( W_k \) is obtained as
\[
W_k = (r_k)_i S_k + u_i + \sum_{j=k+1}^{L} (r_j)_i S_j
\] (26)

We detect the signal from \( S_{L_i} \) to \( S_1 \). When the \( k \)th substream is detected, the last part of equation (26) is zero as \( k \) detected signals have been cancelled. Therefore, the SNR of \( k \)th substream after detection is
\[
\rho_k = \frac{E_s}{L_i N_0} |(r_k)_i|^2, \quad k = 1,2,\ldots,L
\] (27)

We can observe that the order is very important in the processing. If we reorder the detection, i.e. reorder the columns of \( H_{Li+1} \), it will impact the result after the QR decomposition and the system performance. In [15], the authors have proved that in every iteration step of OSIC detection, if we choose to detect the substream with the largest SNR after the last detection, this will optimize the worst-performance substream.

According to above analysis, the SNR of the worst substream after detection is vital for the improvement of the transmission rate of V-BLAST system. Because the CSI is unknown at the transmitter, it is best to equalize the transmission rate of each substream. Therefore, the status of the worst substream would influence the overall throughput. In this case, the outage capacity of V-BLAST system \( C_{\text{out}} \) is
\[
C_{\text{out}} = L_i \log(1 + \min_{i \in [1, L]} \rho_i)
\] (28)
where \( \min_{i \in [1, L]} \rho_i \) is the SNR of the worst substream after detection. Our objective is to maximize the outage capacity, and it is equivalent to select the antennas to maximize \( \min_{i \in [1, L]} \rho_i \) for the V-BLAST system with OSIC.

The detailed algorithm is expressed as follows.

First, instead of the optimal algorithm, we use the suboptimal sorting algorithm [16] to get the detection order by sorting the Euclidean norm of the row vector of \( H_s \). This suboptimal order, denoted by the
permutation $P$, is selected by considering interferences by other substreams.

Then if given detection order, we can obtain the SNR of each substream after the detection using QR decomposition method. The column vectors of $H_{s}$ is sorted based on $P$. The transmit antennas are arranged from right side to left side according to the detection order (i.e. the first detected antenna is arranged to the rightmost), so the QR decomposition of $H_{s,p}$ is

$$H_{s,p} = H_{s}P = Q_{s,p} R_{s,p} \tag{29}$$

When we detect the signals from the transmit antennas, in order to maximize the SNR of the worst substream of all the antenna subsets, the antenna selection criterion is defined as

$$a_{opt} = \arg \max_{a \in A} \{ \min_{k} |(r_{s,p})_{ik}| \} \tag{30}$$

where $a_{opt}$ denotes the optimal transmit antenna subset.

According to the equation (29) and (30), we just need to consider the diagonal elements of $R_{s,p}$ instead of the full QR decomposition. The algorithm could be significantly simplified with the employment of Gram–Schmidt orthogonalization for QR decomposition.

After orthogonalizing the column vector of $H_{s,p}$, we can obtain the orthogonal vector

$$(w_{s,p})_{i} = (H_{s,p})_{i} - \sum_{j=1}^{i-1} k_{ij} (w_{s,p})_{j}, \quad i=1,L,L_{r} \tag{31}$$

where $k_{ij} = \frac{(H_{s,p})_{i}(w_{s,p})_{j}}{(w_{s,p})_{i}(w_{s,p})_{j}}$, $<a,b>$ denotes the inner product of vector $a$ and $b$. It should be noticed that the orthogonalization procedure is performed in an order that the last detected substream is orthogonalized firstly, vice versa. This depend on the fact that when detect the last substream, all other substream has been cancelled, thus the performance of the substream is just concerned with its own channel.

It is easily to prove that the Euclidean norm of $(w_{s,p})_{k}$ is the same as the modular of the diagonal element $(r_{s,p})_{ik}$ for the same detection order.

$$||(w_{s,p})_{i}|| = |(r_{s,p})_{ik}| \tag{32}$$

Therefore the antenna selection criterion described in (30) is equivalent to find the optimal subset specified by the following condition

$$a_{opt} = \arg \max_{a \in A} \{ \min_{k} ||(w_{s,p})_{i}|| \} \tag{33}$$

The following is the comparison of SER between IC-PQRD and maximum the minimum singular value (Max-Min) algorithm [17, 18]. It is difficult to set up an accurate equation to describe the performance of the antenna selection algorithm because the overall performance of the OSIC detection does not depend on single substream only. However, the improvement of the worst-performance substream could enhance the overall performance of the system, so it can inhibit error diffusion in some cases. The Max-Min algorithm is based on zero forcing (ZF) detection, in which each substream is detected independently, and the selection criterion is

$$a_{opt,ZF} = \arg \max_{a \in A} \sigma_{\min} (H_{s}) \tag{34}$$

where $\sigma_{\min} (H_{s})$ is the minimum singular value of $H_{s}$. This algorithm is considered to be optimal with ZF detection, but the order could not make any sense for this algorithm with OSIC detection. It is obvious that

$$\sigma_{\min}^{2} (H_{s}) = \lambda_{\min}^{2} (H_{s} H_{s}^{H}) = \lambda_{\min}^{2} (H_{s} P P^{H} H_{s}^{H}) = \lambda_{\min}^{2} (H_{s} R_{s,p}^{H} H_{s}^{H}) = \sigma_{\min}^{2} (H_{s}) \tag{35}$$

As the eigenvalues of $R_{s,p}$ are all equal to the diagonal elements of it, and $|\lambda_{\min} (G)| \geq |\sigma_{\min} (G)|$ is satisfied for the matrix $G$, we can obtain that

$$\min_{k} |(r_{s,p})_{ik}| \geq \lambda_{\min}^{2} (R_{s,p}) \geq |\lambda_{\min} (R_{s,p})| \geq \sigma_{\min}^{2} (R_{s,p}) = \sigma_{\min}^{2} (H_{s}) \tag{37}$$

According to the above analysis, for the OSIC detection, we can find that the Max-Min algorithm just guarantees the lower limit of the worst substream regardless of the detection order. When the optimal order is utilized, it is possible that the performance of the worst substreams of some unselected subsets is better than that of selected subset. For the V-BLAST system with OSIC, our algorithm considers the effect of order and optimizes the performance of the worst substream.

Deriving from the equation (30) and (33), the computational complexities of IC-PQRD algorithm and Max-Min algorithm are $O(LML_{T})$ and $O(M^{2}L_{r})$, respectively. Obviously, the computational complexity of IC-PQRD algorithm is lower than that of Max-Min algorithm.

IV. NUMERICAL RESULTS

In this section, numerical results are provided to verify the analysis above and the system model $(4,4,8)$ is employed to plot Fig. 2.

First, we simulate the antenna cluster selection algorithm based on the maximum path fading. Assume that the diameter of the cell is $R = 1000m$, the location of the 4 antenna cluster is the centre of each 1/4 area of the cell. The total transmit power is $P$. All the transmit power of the 4 antenna clusters is $P/4$ without antenna

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And the transmit power of the selected antenna cluster is $P$ when the antenna selection algorithm based on maximum path fading is employed. QPSK modulation is adopted and the path loss exponent is 4.0.

Fig. 3 and Fig. 4 show space variation of channel capacity of the proposed antenna cluster selection algorithm and without antenna selection, respectively. Fig. 5 depicts the channel capacity gain of the proposed algorithm. According to these two figures, the channel capacity near the antenna cluster is much higher than that of other areas because MS is closer to the transmit antennas. The channel capacity with antenna cluster selection is higher than that without selection when MS is near the antenna cluster and the four corners of the cell. But in the central region, it shows a negative increase because of the loss of the multiplexing and diversity gain. The average channel capacity with the antenna cluster selection is 7.29bits/s/Hz while that without selection is 8.85bits/s/Hz. The capacity gain is 21.4%.
the SER performance of IC-PQRD, Max-Min and AIA algorithms compared to no selection strategy. We can find that IC-PQRD has better performance than other algorithms. Especially at high SNRs, comparing with Max-Min algorithm, IC-PQRD can reduce SER much faster with lower complexity.

IV. CONCLUSION

In this paper, we proposed a novel two-step antenna selection algorithm for downlink D-MIMO systems and discussed the performance and outage capacity. The simulation results prove that the antenna cluster selection algorithm based on the maximal channel fading could significantly enhance the average channel capacity of downlink distributed antenna systems. Especially, for the cell edge, distinctive improvement in channel capacity and SER is obtained via the antenna cluster selection algorithm. However, for the central region, due to the employment of antenna cluster selection technique, the multiplexing and diversity gain which is achieved from the interaction of multiple transmit antennas is lost. Therefore in this case, the channel capacity and performance are both affected. The IC-PQRD algorithm could evidently improve the outage capacity with low complexity for the V-BLAST system with OSIC. In conclusion, the combination of antenna cluster selection algorithm based on the maximal channel fading and the in-cluster antenna selection algorithm with permutation QR decomposition is a highly effective antenna selection scheme for downlink D-MIMO systems.

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