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Signal Detection Based on Greedy Strategy in MIMO System

[I]Yi Run, [II]Chen Fatang, [III]Tong Qing
[I,II,III]College of Comminication and Information Engineering
[I,II,III]Chongqing Univeristy of Posts and Telecommunications, Chongqing, China

Abstract

Sphere decoding (SD) detection algorithm is commonly used in MIMO system. But, the computational complexity of sphere decoding detection algorithm is restricted by the initial radius and search strategy. In order to reduce the computational complexity of SD detection algorithm, an improved SD detection algorithm which based on greedy strategy (SDBGS) is proposed in this paper. The SDBGS algorithm obeys to the rule of depth-first searching but improves the tree search method of traditional SD algorithm. The SDBGS will sort Euclidean distance of the searching layer and select the nodes which have the minimum Euclidean distance as the signal points. Therefore, SDBGS need not to set the initial radius and each selected signal point is locally optimal with respect to the current layer. The simulation results show that the proposed algorithm can achieve a significant complexity reduction.

Keywords

MIMO; Signal Detection; Sphere Decoding; Greedy strategy

I. Introduction

Now 4G has already became mainstream networks of wireless communication system, and it's characterized by multi-antenna configuration, 100MHz aggregated bandwidth and peak data rate of 3Gbps. However, the introduction of large-scale MIMO (multiple input multiple output) poses greater challenges on the receiving and detection technology while it brings a substantial increase of system capacity and spectral efficiency of 4G/5G[1]. In 4G systems, the number of antennas at sender and receiver increases from four to eight. Due to the influence of multipath propagation and interference between multiple antennas, separating mixed-signal at receiving end is a matter that must be considered in 4G systems, which makes the receiver to accurately recover the sending signals at each sending antennas is facing a big challenge. Recently, the signal detection algorithms in wireless mobile communication system have been hot discussed among industry researchers.

There are many signal detection algorithms are proposed . ML (Maximum likelihood) detection algorithm is optimal detection algorithm among all existing algorithm[2]. Its essence is to traverse all the constellation points that may transmit the signal symbol and take the nearest constellation point as the transmission signal. However,While in large-scale MIMO system, to achieve ML detection signal is too complex to be used in the actual project. Thus, various reduce complexity and ensure performance of signal detection algorithms have been proposed[3]. Such as ZF (Zero Forcing),MMSE (minimum mean square error) detection algorithm and QR decomposition algorithm[4].

Sphere decoding (Spherical Decoding, SD) algorithm, made a very good compromise between performance and complexity. It is a low complexity detection algorithm which can get the maximum likelihood detection performance[5]-[8].At the beginning of decoding, SD algorithm will Set up a super ball with a receive vector as the center, and search over the ball to calculate the maximum likelihood solution. It has the polynomial complexity in the range of the large SNR range. However, the performance of sphere decoding algorithm depends on selection of initial radius[9]. If the initial radius is too large, the search hyper-sphere space will include too many unnecessary points and will lead to increase in complexity, while if the initial radius is too small, there may not be the optimal solution exist within the super ball space and lead to a large reduction in performance. So it is necessary to set the search radius accurately to reduce the complexity of the sphere decoding algorithm and improve the decoding performance[10].

Due to the shortcomings mentioned above, this paper presented a new signal Sphere Decoding detection algorithm which based on greedy strategy (Sphere Decoding Base on Greedy Strategy, SDBGS). SDBGS is a variant of the traditional sphere decoding detection algorithm. It obeys to the rule of depth-first searching but improves the tree search method of traditional SD algorithm .SDBGS will sort Euclidean distance of the layer but will select the nodes which have the minimum Euclidean distance as the signal point instead of searching the constellation from the left to the right. Therefore, SDBGS need not to set the initial search radius and each selected signal point is locally optimal with respect to the current layer.

With the decrease of the number of search points, the computational complexity of the decoding is greatly reduced, and the efficiency of the SDBGS algorithm is greatly improved.

II. MIMO Signal Detection System Model

Consider a MIMO wireless transmission system, the transmitter has M antennas and the receiver has N antennas, where $N \geq M$. Encoded bit stream is mapped to the M-dimensional transmission symbol vector $x \in O^M$, O is the constellation point vector space of sending signals. MIMO system diagram as shown in Figure 1.

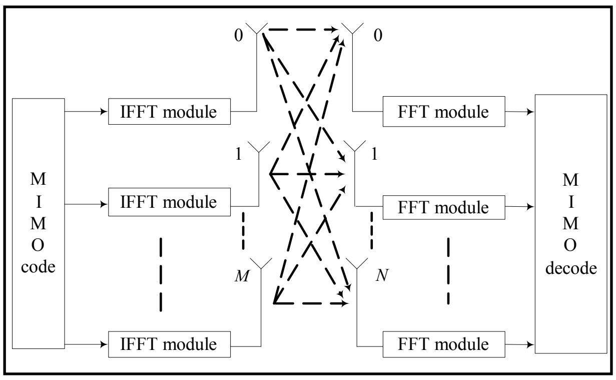

Fig.1: M × N MIMO system diagram

After a flat fading white Gaussian noise channel, the signal received by MIMO system receivers can be described by formula (1):

$$y = Hx + n \tag{1}$$

Where, $\boldsymbol{y}=[y_1, y_2, \cdots, y_N]^T$ is a signal vector of the receiving antenna, $\boldsymbol{x}=[x_1, x_2, \cdots, x_M]^T$ is the transmit signal of the transmitting antenna, Channel matrix H is a M × N dimensional complex matrix , $\boldsymbol{n}=[n_1, n_2, \cdots, n_N]^T$ is the Noise vector and its various components are independent and identically distributed with zero mean and variance of σ^2 Gaussian white noise.

Equation (1) shows $n=y-Hx$ .As the optimal algorithm of MIMO system, ML detection is to get the minimum $\boldsymbol{n}$. The ML is essentially looking for an sending signal constellation point which has a least distance to received signal among the signal constellation point vector space, it is equivalent to an integer domain least squares problem, as shown in the following formula:

$$\boldsymbol{S}_{ML}=\arg\min_{x\in O^M}\|\boldsymbol{y}-\boldsymbol{Hx}\|^2 \tag{2}$$

Where, $\|\bullet\|^2$ is two-norm matrix.

This article for sphere decoding detection algorithm is in terms of the real number system, so it will turn a complex linear system through real value decomposition into an equivalent real linear system. The equation (1) plural form of real value decomposition[4] is the following form: $y=\begin{bmatrix} R(y) \\ I(y) \end{bmatrix}=\begin{bmatrix} R(H) & -I(H) \\ I(H) & R(H) \end{bmatrix}\begin{bmatrix} R(s) \\ I(s) \end{bmatrix}+\begin{bmatrix} R(n) \\ I(n) \end{bmatrix}$
(3)

Where, $R(\bullet)$ and $I(\bullet)$ denote the real and imaginary parts of the complex symbols respectively.

III. SD Detection Algorithm

The core idea of the sphere decoding detection algorithm is described below:

Firstly, the initial search radius ρ_0 of sphere decoding should be calculated , and then set the receiving signal vector as Globe sphere and search within the ball whose radius is ρ_0 .The search paths should be recorded and search radius should be updated immediately according to the distance of the grid points of each dimension. Go round and begin again until there is no grid to be searched within the ball, then the last record of search path is the solution which is required by the system. Sphere decoding is only searching for points inside the inner sphere, thus it avoids the search for the whole grid points, that is the main reason for sphere decoding detect algorithm to reduce complexity largely.

The initial search radius of SD algorithm is defined as formula (4):

$$\rho_0^{\ 2}=\alpha m\sigma^2 \tag{4}$$

Where, m is the dimension of received signal, σ^2 is the Gaussian white noise, α is the Initial radius coefficient and can be calculated by the following formula(5):

$$\int_0^{\frac{\alpha n}{2}}\frac{\lambda^{\left(\frac{n}{2}-1\right)}}{\Gamma\left(\frac{n}{2}\right)}e^{-\lambda}d\lambda=1-\xi \tag{5}$$

Where, $\Gamma(\bullet)$ is the Gamma function, ξ is the probability of a signal point is not found (usually 0.01).

In sphere decoding algorithm, the receiving signal vector space is regarded as a ball and y is the center of the ball.

$$\|\boldsymbol{y}-\boldsymbol{Hx}\|^2\le\rho_0^{\ 2} \tag{6}$$

Wireless transmission channel QR decomposition, $H=QR$, the formula (6) may be rewritten as follows:

$$\begin{aligned}\|\boldsymbol{y}-\boldsymbol{Hx}\|^2&=\|y-QRx\|^2=\|Q^Ty-Rx\|^2\\&=\left\|\begin{bmatrix} Q^T{}_1 \\ Q^T{}_2 \end{bmatrix}y-\begin{bmatrix} R \\ 0_{(n-m)\times m} \end{bmatrix}x\right\|^2\\&=\|Q^T{}_1y-Rx\|+\|Q^T{}_2y\|\le\rho_0^{\ 2}\end{aligned} \tag{7}$$

Set $y^{'}=Q_1^Ty$, $\rho^2=\rho_0^{\ 2}-\|Q_2^Ty\|^2$, Equation (7) can be rewritten as the following formula:

$$\|y^{'}-Rx\|^2\le\rho^2 \tag{8}$$

Expand the formula (8) and get formula (9):

$$\rho^2\ge\sum_{i=M}^{1}\left|y_i^{'}-\sum_{j=i}^{M}r_{i,j}x_j\right|^2 \tag{9}$$

Part of the Euclidean distance is:

$$T_l=\sum_{i=M}^{l}\left|y_l^{'}-\sum_{j=l}^{M}r_{l,j}x_j\right|^2 \tag{10}$$

The relationship between the part Euclidean distance and adjacent nodes:

$$T_l=T_{l+1}+\left|y_{l+1}^{'}-\sum_{j=l+1}^{M}r_{l+1,j}x_j\right|^2 \tag{11}$$

MIMO signal detection problem can be seen as tree searching which has M layers, searches all the leaf nodes to find the leaf node which has minimum Euclidean distance to root node. Figure 2 shows the search tree of the sphere decoding algorithm in QPSK modulation.

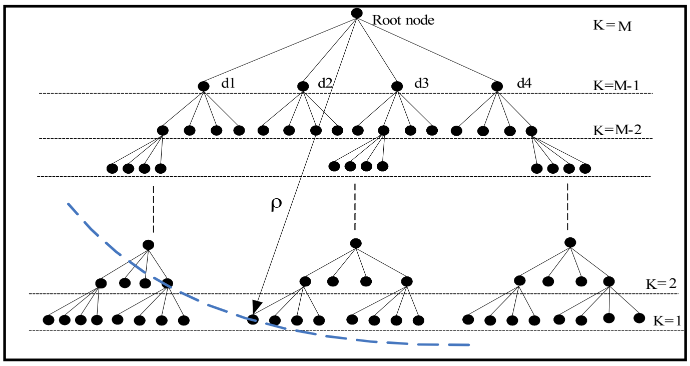

Fig.2: search tree of SD detection algorithm in QPSK

The starting position for the search is the first signal on the M layer, and then ,search the nodes layer by layer until k=1, which indicates that the leaf nodes have been searched. If the distance increment is less than the length of the initial radius ρ_0, records this search path and update search radius ρ, and then restart the search. If the distance increment of a dimension greater than the radius ρ, it stops searching any grid nodes after the point, back to the next node on the previous dimension and continue the search, until there is no grid to be searched within the ball, then the last record of search path is the solution which is required by the system.

From the above analysis, sphere decoding algorithm needs to solve two problems: first, how to select an appropriate initial search radius. If the initial radius is too large, the search hyper-sphere space will include too many unnecessary points, while if initial radius is too small, the optimal solution may not be exist within the super ball space. Second, how to find the nearest point from the received vector quickly.

The traditional SD algorithm uses a depth-first search manner, in accordance with the order of the signal constellation points, from the left to the right to enumerate all the constellation points. Obviously in this manner, the convergence of radius is very slow, and lots of signal grids need to searched, so it is difficult to find the nearest point from the received vector quickly.

In this paper, in order to overcome the problems of SD detection algorithm, an improved SD detection algorithm which based on greedy strategy (SDBGS) is proposed. It is not only insensitive to the initial radius but also can reduce the number of search signals that make the radius convergence quickly.

IV. SDBGS Detection Algorithm

Greedy strategy means that the overall optimal solution can be achieved through a series of local optimal choice. Greedy algorithms are usually in top-down manner and in an iterative manner to make successive greedy choice, every choice will make the greedy desires problem to a smaller scale problems.

To address this shortcoming of greedy strategy, we propose the following improvements: the part of Euclidean distance between nodes on each level to the lower layer node to be sorted. Then, selected the node which has the minimum Euclidean distance as the optimal node of current layer and continue.

Here we will learn about the process of sphere decoding detection algorithm based on greedy strategy (SDBGS).

SDBGS obey to the rule of depth-first searching, but selects the nodes which has minimum Euclidean distance instead of beginning the searching from the left to the right. Each selected signal point is relative to the current layer is locally optimal.

Details are as follows:

Begins at M layer, computes the Euclidean distance between y_M and X_M:

$$T(y_M, R_{M,M}X_1), T(y_M, R_{M,M}X_2), T(y_M, R_{M,M}X_i), ..., T(y_M, R_{M,M}X_{2^r}) \quad (12)$$

Then sort the distance from small to large:

$$T(y_M, R_{M,M}X_{i_1}) < T(y_M, R_{M,M}X_{i_1}) < T(y_M, R_{M,M}X_{i_i}) < L < T(y_M, R_{M,M}X_{i_{2^r}}), \quad (i_1, i_2, ..., i_{2^r} \in 2^r) \quad (13)$$

Select X_{i_1} which has the minimum distance $T(y_M, R_{M,M}X_{i_1})$ as the signal node on M layer. Continue the searching to next layer and the process is similar to the above process. If the distance on some layer is bigger than the radius, then the left nodes on this layer is no longer needed to search and go back to the previous layer to continue the searching at the next node. If the search has reached the last layer, and the sum of all parts of Euclidean distances are less than ρ, then record the search path and replace the radius with the sum of Euclidean distances of this path.

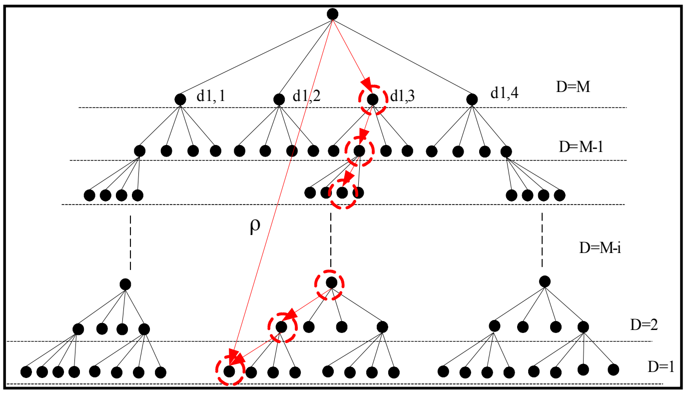

Fig.3: The search tree of SDBGS in QPSK modulation

As shown in figure 3, the points in red circle has the closest distance to the sender node in this search, namely the minimum-distance constellation points, we select a constellation point which has the minimum distance increments to search down at each time.

The SDBGS algorithm steps in QPSK modulation are as follows:

Step1: From the M layer begins, the root node stands for the received signal vector. It has four branches. Part of the Euclidean distance between the root node and these four symbols are defined as $d_{1,i}$. where $i = 1,2,3,4$.

Step 2: Sort the part of the Euclidean distance $d_{1,i}$ and select the minimum d'_1, which satisfies:

$$d'_1 <= d_{1,i} \quad i = 1,2,3,4 \quad (14)$$

Analyzing the following formula is established:

$$\sum_{k=1}^{M} d'_k < r \quad (15)$$

If the formula (15) holds, then save this node and part of the Euclidean distance d'_1.In this case, proceeds to the next layer, and $d_{m,i}$ stands for part of the Euclidean distance between the nodes on m+1 layer and those on m layer.

Step 3: Similarly, sort the $d_{m,i}$ achieved by the previous step and repeat step2.

Step 4: If current layer is the last one, namely the leaf-node layer, then this path reserved is just the needed signal vector .Otherwise repeat step 3.

V. Numerical Results And Simulation Analysis

In this paper, the simulation parameters of SDBGS in LTE-A system are shown in Table 1. It should be noted that this article compare the complexity and performance of two different algorithms under three different modulation schemes and three different antenna configurations. And the complexity of the algorithm is measured by the number of visited nodes.

Table 1: Simulation parameters

Simulation parameters	Number
Modulation scheme	QPSK/16QAM/64QAM
System bandwidth	5MHz 25RB
System Model	Error Vector Magnitude
CP Type	Normal
Antenna configuration	$4 \times 4 / 8 \times 8$

The comparison of figure 4 and figure 5 show that in the same of SNR and modulation schemes, the performance of traditional SD detection algorithm and SDBGS algorithm in 8x8 MIMO is lower than that in 4x4 MIMO. But, since the SDBGS algorithm only sort the Euclidean distance of the searching layer and improve the tree search method of traditional SD algorithm, the performance of the SDBGS algorithm is almost identical to traditional SD algorithm.

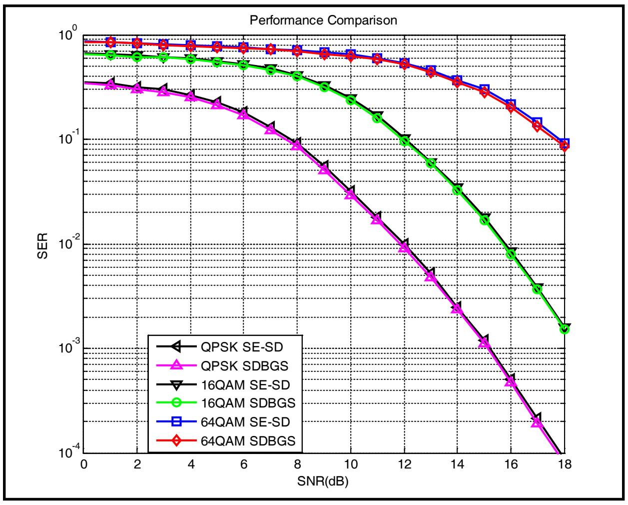

Fig.4: Performance Comparison of 4×4 MIMO

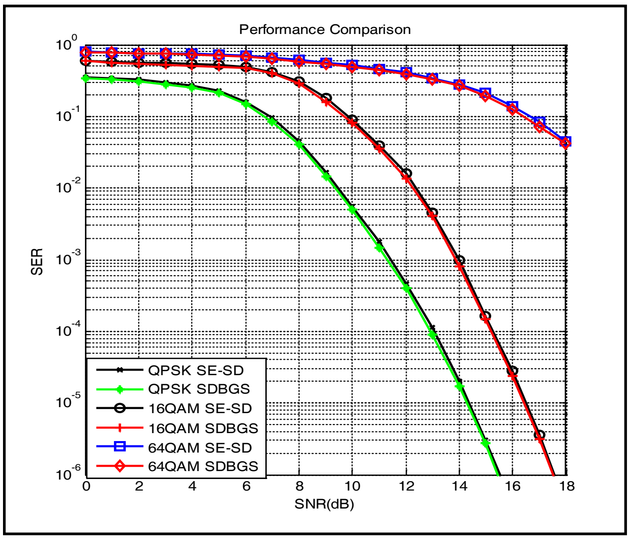

Fig.5: Performance Comparison of 8×8 MIMO

As can be seen from Figure 6 and Figure 7, the complexity of SDBGS compared to conventional SD algorithm can have different degrees of reduction, especially in the low SNR region. For the 4x4 MIMO systems, the detection complexity of SDBGS in QPSK modulation compared to conventional SD algorithm is reduced by 27%, the detection complexity in 16QAM modulation is reduced by 27%, and in 64QAM modulation the detection complexity is reduced by nearly 50%. Therefore, in the case of high order modulation, SDBGS algorithm has higher system gain.

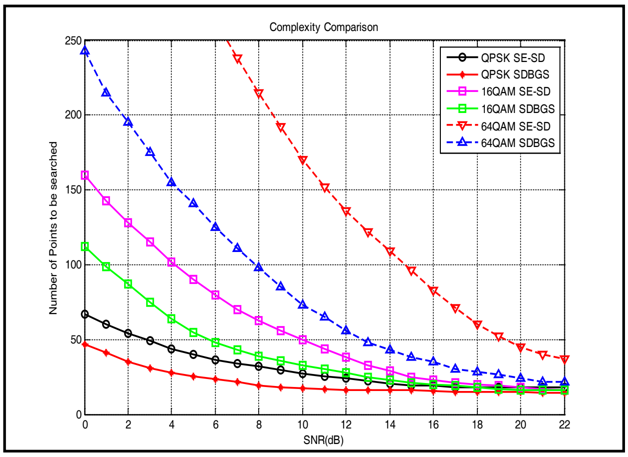

Fig.6: Complexity Comparison of 4×4 MIMO

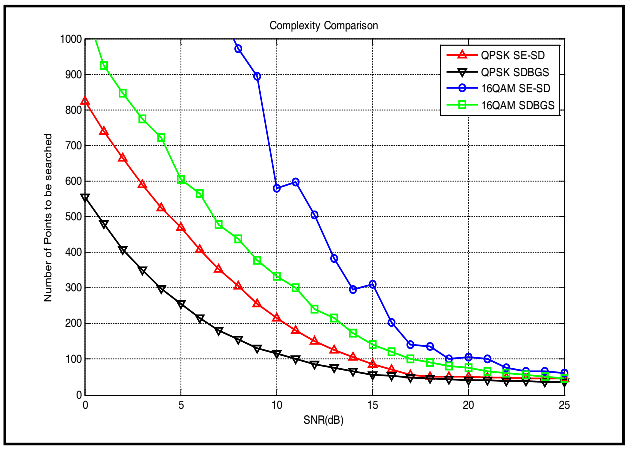

Fig.7: Complexity Comparison of 8×8 MIMO

The simulation results show that, compared to conventional SD detection algorithm, the SDBGS algorithm presented in this paper has the advantage of low complexity, especially in the case of low SNR and high-order modulation. Therefore, the efficiency of the SD algorithm is greatly improved.

VI. Conclusion

The SD algorithm is a low complexity detection algorithm which can get the maximum likelihood detection performance. But, in the case of low SNR and high-order modulation, the detection complexity of the SD algorithms is very high. This paper presents a SDBGS algorithm, which is a variation of depth-first SD detection algorithm. SDBGS will sort Euclidean distance of the searching layer and select the nodes which have the minimum Euclidean distance as the signal points. That will reduce a great number of search points and speed up the convergence rate of the search radius. Therefore, the computational complexity of the decoding is greatly reduced.

The simulation results show that, compared to conventional SD detection algorithm, the complexity of SDBGS is extremely low, especially in the case of low SNR and high-order modulation. Therefore, the efficiency of the SDBGS algorithm is greatly improved.

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