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Approximate ML Detection with the Best Channel Matrix Selection for MIMO Systems

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Abstract – In this paper, a best channel matrix selection scheme (BCMS) is proposed to approximate maximum likelihood (ML) detection for a multiple-input multiple-output system. For a one stage BCMS scheme, one of the transmitted symbols is selected to perform ML detection and the other symbols are detected by zero forcing (ZF). To increase the diversity of the symbols that are detected by ZF, multi-stage BCMS detection scheme is used to further improve the system performance. Simulation results show that the performance of the proposed BCMS scheme can approach that of ML detection with a significant reduction in complexity.

Keywords: MIMO, Maximum Likelihood Detection, Zero Forcing, Best Channel Matrix Selection

1. Introduction

Recently, the application of multiple-input multiple-output (MIMO) antenna systems and space-time signal processing techniques to wireless communication systems has become an important issue [1]-[2]. By employing multiple antennas, one can increase data rates significantly as well as improve performance. Possible detection techniques include zero-forcing (ZF), minimum mean-square error (MMSE) detection, Vertical Bell Laboratories Layered Space Time (V-BLAST) [3] detection and maximum-likelihood detection (ML) [4]. Among these schemes, ML is optimal but its complexity is exponential in the number of transmit antennas, which makes it infeasible when the number of transmit antennas is large. As a result, some effort has gone into developing suboptimum ML schemes that provide similar performance but with less complexity.

In order to reduce such high complexity, many low complexity detection algorithms based on V-BLAST principle have been proposed, but almost all of these algorithms will reduce error performance greatly due to error propagation [5]-[6]. In order to overcome such shortcoming, some joint ML detection and V-BLAST decoding algorithms for MIMO system have also been presented, which could improve the diversity order for the several layers and thereby the entire system performance could be enhanced effectively [7]-[8]. However, these improved V-BLAST schemes based detection methods only implement a tradeoff between complexity and performance and still cannot exploit the maximum diversity gain and achieve the best error performance.

Usually, two kinds of measures can be adopted to reduce the decoding complexity and implement fast decoding. One is to reduce the search times in the decoding process, such as sphere decoding (SD) methods [9]. But in the case that the number of transmit antennas is not large or the modulation order is low, the advantage of SD is not obvious while comparing with ML detection. The other is to save multiplication operations during each search step [10]-[11].

In this paper, we propose an approximate ML detection with the best channel matrix selection (BCMS) for MIMO systems. In the proposed scheme, with the best channel matrix selection, we select one symbol to perform ML detection, and the other symbols are processed by ZF detection. Since the ML detected symbol has full diversity, the error propagation from this sub-stream to the other sub-streams can be minimized. To increase the diversity of the symbols that are detected by ZF, the multi-stage detection is used to further improve the performance of the proposed BCMS scheme.

The remainder of this paper is organized as follows. Section II describes the system model. In Section III, the proposed BCMS scheme is described. The simulation results are presented in Section IV. Complexity analysis and conclusions will be given in Section V and Section VI, respectively.

2. System Model

We consider a general MIMO architecture with M

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transmit and N receive antennas. Only uncoded systems are considered in this paper. At the transmitter side, the data stream is demultiplexed into M sub-streams, and each sub-stream is transmitted from an antenna independently and simultaneously. At the receiver side, each receive antenna receives the signals from all M transmit antennas. We adopt the quasi-static block fading wireless channel model, so that the path gains are constant over a frame, and vary from frame to frame. In such a system, the received data can be modeled as:

$$\mathbf{r}=\mathbf{Hs}+\mathbf{n}\,, \tag{1}$$

where $\mathbf{r}$ is $N\times 1$ receive data vector, $\mathbf{H}$ is $N\times M$ channel matrix, $\mathbf{s}$ is $M\times 1$ signal vector, and $\mathbf{n}$ is the $(N\times 1)$ complex additive white Gaussian noise (AWGN) vector. The noise vector $\mathbf{n}$ is independent and identically distributed (i.i.d), each element having a variance of σ^2. Assuming the antennas are placed sufficiently apart from each other, the channels will be uncorrelated with each other. At the receiver, with estimated channel knowledge of $\mathbf{H}$, the transmitted signal $\mathbf{s}$ is detected from $\mathbf{r}$. In this paper, perfect channel estimation is assumed. Note that we assigned equal average power among all transmit antennas, and the total power is normalized to 1.

In order to achieve the best error performance, the best decoding method is to employ ML detection algorithm as presented in (2).

$$\bar{\mathbf{s}}_i = \arg\min_{\mathbf{s}_i \in \mathrm{C}} \left\|\mathbf{r}-\mathbf{Hs}_i\right\|^2,\ i=1,2,\ldots,Q^{\mathrm{M}} \tag{2}$$

where C is the set formed by all possible codes and Q is the cardinality of the modulation constellation set. $\|.\|$ denotes the norm operator. While the number of transmit antennas or the modulation order of constellation symbols increases rapidly, the size of set C will be very large and so ample time must be spent in searching the optimal ML point. In order to solve such a deficiency and implement real time decoding at the receiver, it is necessary to design an approximate ML detection algorithm with low complexity and high system performance.

3. Best Channel Matrix Selection

The key idea of the proposed BCMS scheme is that some symbols are selected to perform ML detection, and the other symbols are processed by zero forcing (ZF) detection. We describe the one stage BCMS scheme firstly, and then we extend the one stage BCMS scheme to multi-stage detection. The detailed processes of one stage will be explained below.

3.1 Determine the Nulling Matrix with Maximum SNR

In this step, we construct M sub-matrixes by excluding the k_1-th (k_1=1,…,M) column of channel matrix $\mathbf{H}$. Each constructed sub-matrix $\mathbf{H}_{k_1}$ with N×(M-1) dimensions and the Zero Forcing (ZF) nulling matrix $\mathbf{G}_{k_1}$ is calculated as

$$\mathbf{G}_{k_1} = \left(\mathbf{H}_{k_1}^H \mathbf{H}_{k_1}\right)^{-1} \mathbf{H}_{k_1}^H, \tag{3}$$

where k_1=1,2,…,M, sub-matrix $\mathbf{H}_{k_1}$ denotes k_1-th sub-matrix of the first stage, and $\mathbf{H}_{k_1}^H$ denotes the Hermitian of matrix $\mathbf{H}_{k_1}$. The post-detection SNR for nulling matrix $\mathbf{G}_{k_1}$ is given by

$$\rho_{k_1} = \sum_{u=1}^{M-1} |s|^2 /(\sigma^2 \left\|w_{k_1,u}\right\|^2), \tag{4}$$

where $|s|^2$ is the transmitted symbol power for each antenna, $w_{k_1,u}$ denotes the u-th row of nulling matrix $\mathbf{G}_{k_1}$. The maximum post-detection SNR can be found as

$$\rho_{j_1} = \arg\max_{1\le k_1\le \mathrm{M}}(\rho_{k_1}). \tag{5}$$

It means if the sub-matrix is constructed by excluding the j_1-*th* column of channel matrix $\mathbf{H}$, we can get maximum post-detection SNR for the other transmitted symbols.

3.2 Determine Candidate Symbol Combinations

With the maximum post-detection SNR ρ_{j_1}, we select the nulling matrix $\mathbf{G}_{j_1}$. To obtain a candidate symbol combination, we should determine one probable symbol from j_1-th transmit antenna and M-1 symbols from the other antennas. When we determine these M-1 symbols, the probable transmitted symbol from j_1-th transmit antenna is considered as interference. Hence we subtract this interference from the received signal vector $\mathbf{r}$, and then the modified received signal vector is multiplied by $\mathbf{G}_{j_1}$. The tentative transmitted signal vector except the symbol from j_1-th transmit antenna can be obtained as

$$\tilde{\mathbf{s}}_{j_1}^q = \mathbf{G}_{j_1}\left(\mathbf{r}-\mathbf{h}_{j_1} s_{j_1}^q\right),\ q=1,\ldots,Q \tag{6}$$

where $\mathbf{h}_{j_1}$ denotes the j_1-th column of channel matrix $\mathbf{H}$,

$s^q_{j_1}$ is the q-th ($1 \le q \le 4$ for QPSK modulation, $1 \le q \le 16$ for 16 QAM modulation and so on) probable symbol that is transmitted from j_1-th antenna for the first stage detection. And we make decision for the vector $\tilde{\mathbf{s}}^q_{\bar{j}_1}$

$$\mathbf{s}^q_{\bar{j}_1} = \mathbf{Dec}\left(\tilde{\mathbf{s}}^q_{\bar{j}_1}\right), \tag{7}$$

where $\mathbf{Dec}(\cdot)$ denotes the decision (slicing) operation associated with a modulation scheme. Using symbol $s^q_{j_1}$ and vector $\mathbf{s}^q_{\bar{j}_1}$, we can construct a candidate symbol combination corresponding to the probable symbol $s^q_{j_1}$ as

$$\mathbf{s}^q_{j_1} = \begin{cases} \left(s^q_{j_1}, \mathbf{s}^q_{\bar{j}_1}\right) & \mathit{for}\ j = 1 \\ \left(\mathbf{s}^q_{\bar{j}_1}(1), \ldots, \mathbf{s}^q_{\bar{j}_1}(j-1), s^q_{j_1}, \mathbf{s}^q_{\bar{j}_1}(j), \ldots, \mathbf{s}^q_{\bar{j}_1}(\mathbf{M}-1)\right) & \mathit{for}\ 1 < j < \mathbf{M} \\ \left(\mathbf{s}^q_{\bar{j}_1}, s^q_{j_1}\right) & \mathit{for}\ j = \mathbf{M} \end{cases} \tag{8}$$

3.3 Select Final Decision Value by Likelihood Test

From step 3.2, we obtained Q candidate symbol combinations, and one symbol combination maximizing the likelihood will be selected among them.

$$\bar{\mathbf{s}}_{j_1} = \arg\min_{1 \le q \le Q} \left\| \mathbf{r} - \mathbf{H}\mathbf{s}^q_{j_1} \right\|^2 \tag{9}$$

As mentioned above, for one stage BCMS scheme, the selected j_1-th symbol is detected by ML detection. It can achieve full diversity gain N, however, diversity gain of the other ZF detected symbols is N-M+2. Therefore, the system performance highly depends on the detection accuracy of the other M-1 ZF detected symbols. To improve the detection accuracy of these symbols, multi-stage detection for BCMS scheme can be used to further improve the system performance.

For P (1≤ P ≤ M) stages BCMS detection, at the p-th (1≤ p ≤ P) stage, the symbols detected by ML detection in previous stages are $s^{c_1}_{j_1}, s^{c_2}_{j_2}, \cdots, s^{c_{p-1}}_{j_{p-1}}$. To detect $s^{c_p}_{j_p}$, we first determine the nulling matrix $\mathbf{G}_{j_p}$ with maximum post-detection SNR and $\mathrm{N} \times (\mathrm{M}\text{-}p)$ dimensions similar to step 3.1. Each probable $s^q_{j_p}$ and the vector $\mathbf{s}^{c_{p-1}}_{j_{p-1}} = \left[s^{c_1}_{j_1}, s^{c_2}_{j_2}, \cdots, s^{c_{p-1}}_{j_{p-1}}\right]$ detected by ML in previous stages are cancelled from the received signal vector $\mathbf{r}$. After the nulling process, the modified vector $\mathbf{s}^q_{\bar{j}_p}$ is obtained. $s^q_{j_p}$ and $\mathbf{s}^{c_{p-1}}_{j_{p-1}}$ are then merged into $\mathbf{s}^q_{\bar{j}_p}$. Similar to (8), the merged vectors are then ordered according to the transmitted antenna number to get a candidate symbol combination $\mathbf{s}^q_{j_p}$. Finally, the symbol combination maximizing the likelihood will be selected among the candidate symbol combinations.

Unlike ML detection scheme which calculates the distance metrics for all possible QM symbol combinations, the proposed scheme only calculates the distance metrics for PQ candidate symbol combinations.

4. Simulation Results

In this section, the performance of the proposed detection scheme is evaluated and compared with that of the ML and V-BLAST schemes. QPSK constellation is used for all transmitters and ZF nulling method is employed. The channel matrix is assumed constant over a frame, and varies from frame to frame. We also assume that the delay spread of each channel is negligible. Moreover, we assume that the perfect channel state information (CSI) is available at the receiver.

Fig.1 shows the BER performance in the M=N=4 case. Compared with V-BLAST, it can be observed that the BER curves of the proposed scheme more approach that of the ML scheme. When P=1, the required SNR of the proposed scheme for achieving the BER of 10^{-4} is 2.3dB better than that of the ML detection scheme. In this case, one sub-stream gets full diversity and the other sub-streams have diversity order N-M+2. When P=2, the BER performance of the proposed scheme is about 1.2dB worse than that of ML, because the two sub-streams can get full diversity and the other M-2 sub-streams have diversity order N-M+3.

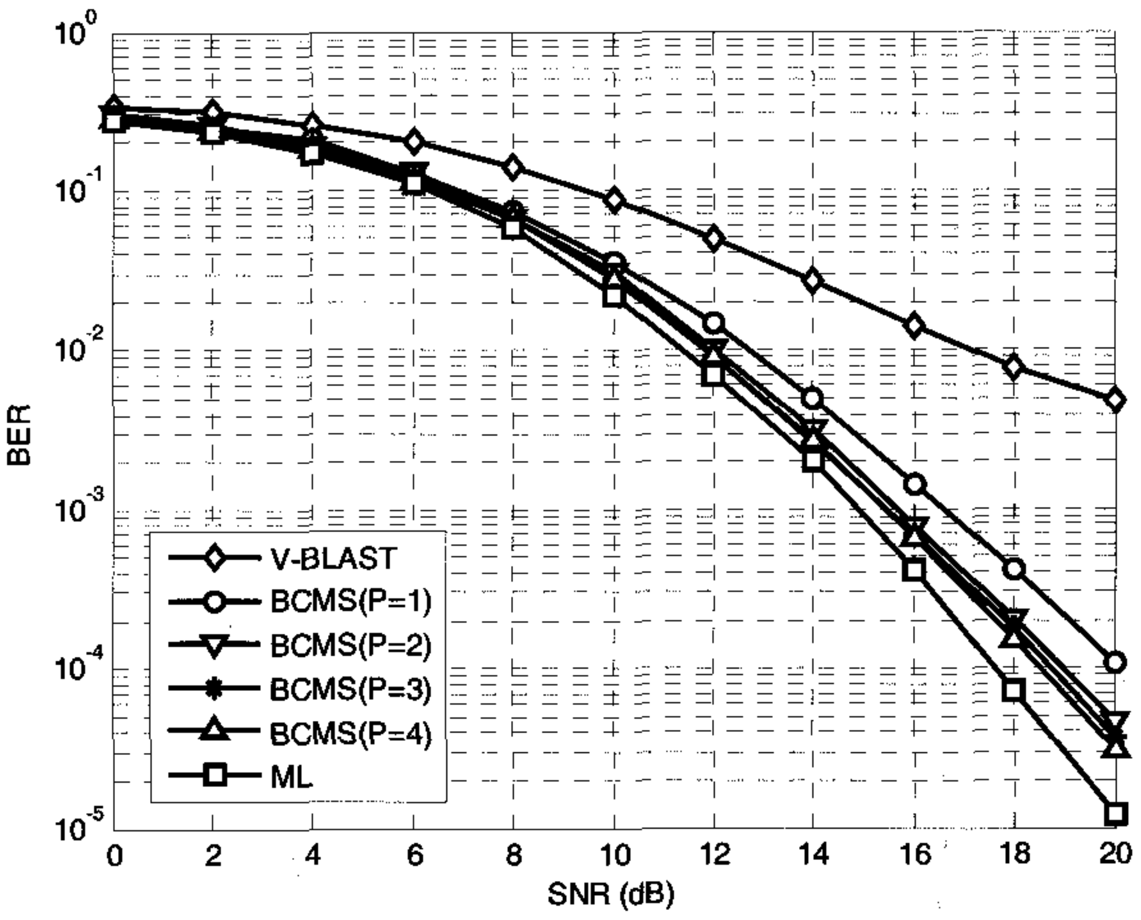

Fig. 1. BER performance of V-BLAST, BCMS and ML for (4,4) MIMO system using QPSK modulation.

Two-stage BCMS can achieve better performance than that of one-stage BCMS. Due to the error propagation from stage one and stage two, when P=3 and P=4, the BER performance of the proposed scheme is similar to that of the two-stage BCMS.

5. Complexity Analysis

Unlike ML detection, the proposed multi-stage detection scheme calculates the distance metrics for only PQ candidate symbol combinations. The algorithmic complexities of V-BLAST, ML detection, and the proposed schemes are compared by arithmetic operations as shown in Table 1. If we use QPSK modulation and N=M=4, for one, two, three, and four stage BCMS schemes, the complexity is reduced by 94.46%, 90.63%, 87.04%, and 82.84% from conventional ML detection, respectively. And the complexity of the proposed multi-stage schemes increases about 35.11%, 61.67%, 72.29%, and 79.07% over V-BLAST, respectively. If the high level modulation and/or greater number of transmit antenna is used, we can get greater complexity reduction from ML detection using the proposed BCMS scheme.

6. Conclusion

In this paper, an approximate ML detection scheme is proposed for MIMO systems. The proposed scheme only calculates the PQ Euclidean distance of the candidate symbol combinations instead of all possible symbol combinations. It achieves much lower computational complexity compared to the ML detection scheme, especially for many transmit antennas and/or high order modulation. Furthermore, the proposed scheme can provide the approximate ML performance.

Table 1. Complexity comparison of V-BLAST, ML detection and the proposed BCMS

Algorithms	Arithmetic operations
V-BLAST	$\sum_{p=1}^{M}\left[\frac{4}{3}(M\text{-}p+1)^3+(18N+\frac{1}{2})(M\text{-}p+1)^2 +(10N-\frac{29}{6})(M\text{-}p+1)+(13N-3)\right]$
ML detection	$Q^{2M}/2+(9NM+10N-1/2)Q^M-1$
The proposed BCMS	$\sum_{p=1}^{P}\left[\frac{4}{3}(M\text{-}p)^4+(18N+\frac{4}{3})(M\text{-}p)^3+(28N-\frac{23}{6}) (M\text{-}p)^2+[(9N-2)Q+10N-\frac{23}{6}](M\text{-}p)+ (9NM+16N)Qp+(\frac{Q^2-Q}{2}-1)p-1\right]$

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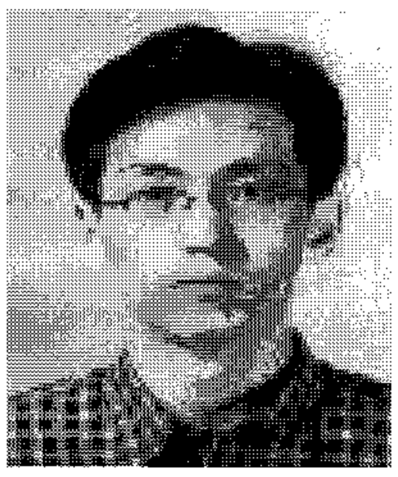

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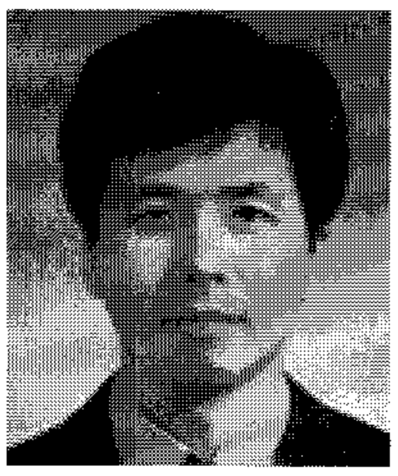

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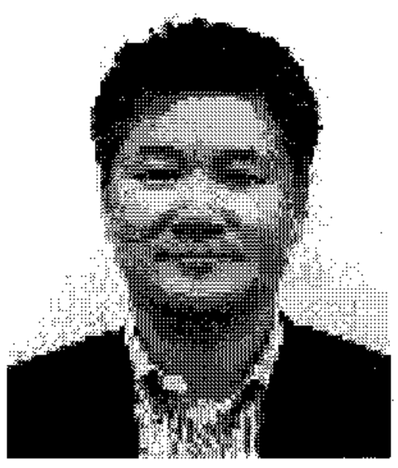

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