LETTER

An Improved Low Complexity Detection Scheme in MIMO-OFDM Systems*

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SUMMARY Although the QR decomposition M algorithm (QRD-M) detection reduces the complexity and achieves near-optimal detection performance, its complexity is still very high. In the proposed scheme, the received symbols through bad channel conditions are arranged in reverse order due to the performance of a system depending on the detection capability of the first layer. Simulation results show that the proposed scheme provides almost the same performance as the QRD-M. Moreover, the complexity is about 33.6% of the QRD-M for a bit error rate (BER) with 4×4 multi input multi output (MIMO) system.

key words: *MIMO-OFDM, lattice reduction aided detection, V-BLAST*

1. Introduction

Orthogonal frequency division multiplexing (OFDM) is a modulation method to mitigate the bad influence about the multipath. OFDM converts a frequency selective channel into a narrowband frequency flat sub-channels so that a per subcarrier equalizer can much more easily be designed in practice than a time-domain equalizer [1].

OFDM-based transmission systems can be extended to a MIMO architecture [2]. MIMO-OFDM using spatial division multiplexing (SDM) scheme is regarded as a promising solution to enhance the performance in rich a scattering wireless channel [3].

The vertical bell laboratories layered space time (V-BLAST) [4] is an effective MIMO architecture to provide spatial multiplexing and receiver diversity gain. Several detection algorithms have been proposed for V-BLAST system. The linear detection schemes such as zero-forcing (ZF) and minimum mean square error (MMSE) are popular way to detect the transmitted signal with low complexity. But, the linear detection schemes have the worst performance among MIMO detection schemes for noise enhancement. The ordered successive interference cancellation (OSIC) detection scheme has better error performance than linear detection. Because the accurate detection of the first layer improves overall system performance in the OSIC detection, the performance depends on initial layer detection capability. However, the OSIC detection has wide gap error performance compared with the optimum error performance detection scheme. Among MIMO-OFDM detection schemes, maximum likelihood detection (MLD) scheme has the best error performance for V-BLAST system. However, the complexity of MLD is exponentially increased by the number of transmission antennas and the constellation level. Therefore, MLD can not be used for practical implementation for complexity, although it achieves high transmit data rate due to good error performance. To reduce the MLD complexity, the QRD-M scheme which has comparable performance to ML scheme is proposed [5]. Although the QRD-M detection reduces the complexity by selecting M candidates and achieves near ML detection performance, the detection complexity of this scheme is still highly increased by the number of transmit and receive antennas, constellation level [6].

Recently, the lattice-reduction-aided detection (LRD) schemes [7], [8] have been proposed to enhance the performance without the increased complexity for MIMO system. Although LRD scheme can achieve near MLD performance with low complexity, it is still unable to approach optimal performance.

As a result, MLD has the optimal BER performance. However, it is difficult to use MLD because MLD has the very high complexity. Similarly, although QRD-M has the higher BER performance than other schemes as Linear, OSIC and LRD, it has the higher complexity than the others except for MLD. But the complexity of QRD-M is not as high as the complexity of MLD. So, the proposed scheme is suggested in order to correct the flaw of the QRD-M.

In the proposed scheme, the received symbols through bad channel conditions are arranged in reverse order due to the performance of system depending on detection capability of the first layer. Afterward, V probable symbols are detected at the first layer and rest layers except for the first layer are detected with complex Lenstra-Lenstra-Lovasz (CLLL) algorithm. Finally the most probable stream is selected through a ML test. The proposed scheme can achieve lower complexity than QRD-M.

2. System Model

To increase the data rate of the wireless communication, N_T transmitter and N_R receiver antennas in MIMO-OFDM system with spatial multiplexing are considered. The OFDM symbol of m-th transmit antenna is represented as $\mathbf{X}_m = [X_m^{(0)}, X_m^{(1)} \ldots, X_m^{(K-1)}]$, where K is the number of subcarriers in one OFDM symbol and $X_m^{(K)}$ denotes the complex gain

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of *k-th* subcarrier. After a data stream is divided into N_T substreams, the MIMO-OFDM transmitter performs an inverse fast Fourier transform (IFFT) and appends the cyclic prefix (CP) at each transmission symbol simultaneously. It is assumed that CP length is longer than maximum length of channel impulse response to prevent intersymbol interference (ISI). The MIMO-OFDM receiver performs reverse process. The received signal model can be written as

$$\mathbf{Y}^{(k)} = \sum_{i=1}^{N_R}\sum_{j=1}^{N_T} H_{i,j}^{(k)} \cdot X_j^{(k)} + N_i^{(k)} = \mathbf{H}^{(k)}\cdot\mathbf{X}^{(k)} + \mathbf{N}^{(k)}, \quad (1)$$

where j and i are transmit and receive antenna index respectively. $\mathbf{X}^{(k)}$ and $\mathbf{Y}^{(k)}$ are the transmitted and received symbol vector respectively. $\mathbf{N}^{(k)}$ is the zero mean circularly symmetric complex Gaussian noise at the ith receive antenna and its variance is σ_n^2. Finally, $\mathbf{H}^{(k)}$ is an $N_R \times N_T$ independent and identically distributed (i.i.d) random complex matrix of multipath channel.

3. Conventional Lattice-Reduction-Aided Scheme

The channel matrix with large condition number has low performance because it amplifies noise for estimated transmit symbols. If the channel condition number is small, detection ability is increased. LRD scheme uses the reduced condition number of channel to estimate transmitted symbols. It uses Lenstra-Lenstra-Lovasz (LLL) method to reduce the channel condition number.

3.1 LLL Algorithm

The LLL algorithm is performed with real-value channel matrix and received symbols are as follows

$$\mathbf{H} = \begin{bmatrix} \mathrm{Re}(\mathbf{H}) & -\mathrm{Im}(\mathbf{H}) \\ \mathrm{Im}(\mathbf{H}) & \mathrm{Re}(\mathbf{H}) \end{bmatrix},$$
$$\mathbf{X} = \begin{bmatrix} \mathrm{Re}(\mathbf{X}) \\ \mathrm{Im}(\mathbf{X}) \end{bmatrix}, \mathbf{Y} = \begin{bmatrix} \mathrm{Re}(\mathbf{Y}) \\ \mathrm{Im}(\mathbf{Y}) \end{bmatrix}. \quad (2)$$

LLL algorithm is based on QR decomposition of channel matrix. A new channel matrix $\widetilde{\mathbf{H}}$ with QR decomposition is as follows

$$\widetilde{\mathbf{H}} = \widetilde{\mathbf{Q}}\widetilde{\mathbf{R}} = \mathbf{HT}, \quad (3)$$

where $\mathbf{T}$ with determinant ± 1 is unimodular matrix. $\widetilde{\mathbf{H}}$ with low condition number has more orthogonal matrix than original channel matrix $\mathbf{H}$. The original channel matrix $\mathbf{H}$ and new channel matrix $\widetilde{\mathbf{H}}$ have same lattice. Consequently, a new channel matrix $\widetilde{\mathbf{H}}$ may achieve a smaller condition number and better performance results than $\mathbf{H}$.

3.2 LR-Aided Detection

The conventional LRD uses linear detection scheme. Linear scheme with $\mathbf{H}$ gives low diversity order but LRD scheme achieves the maximum receive diversity. A new matrix $\widetilde{\mathbf{H}}$ is given as Eq. (3). By using this relation in Eq. (1), it is rewritten as follows

$$\mathbf{Y} = \mathbf{HTT}^{-1}\mathbf{X} + \mathbf{N} = \widetilde{\mathbf{H}}\mathbf{T}^{-1}\mathbf{X} + \mathbf{N} = \widetilde{\mathbf{H}}\mathbf{Z} + \mathbf{N}, \quad (4)$$

where $\mathbf{Z} = \mathbf{T}^{-1}\mathbf{X}$. The vector $\mathbf{Y}$ is multiplied by the Moore-Penrose pseudo-inverse of the channel matrix $\widetilde{\mathbf{H}}^{+}$ of the reduced channel matrix $\widetilde{\mathbf{H}}$.

$$\overline{\mathbf{Z}} = \widetilde{\mathbf{H}}^{+}\mathbf{Y} = \mathbf{T}^{-1}\mathbf{X} + \overline{\mathbf{N}} = \mathbf{Z} + \overline{\mathbf{N}}, \quad (5)$$

where $\overline{\mathbf{N}} = \widetilde{\mathbf{H}}^{+}\mathbf{N}$. The ZF $\widetilde{\mathbf{H}}^{+}$ matrix is determined as

$$\tilde{\mathbf{H}}_{ZF}^{+} = (\widetilde{\mathbf{H}}^{H}\widetilde{\mathbf{H}})^{-1}\widetilde{\mathbf{H}}^{H}, \quad (6)$$

and the MMSE $\widetilde{\mathbf{H}}^{+}$ matrix is

$$\tilde{\mathbf{H}}_{MMSE}^{+} = (\widetilde{\mathbf{H}}^{H}\widetilde{\mathbf{H}} + \sigma_n^2\mathbf{I})^{-1}\widetilde{\mathbf{H}}^{H}, \quad (7)$$

where $\mathbf{I}$ is an identity matrix and $(\cdot)^H$ is the conjugate transpose operation. The estimated symbols $\mathbf{Z}$ is as follows

$$\widehat{\mathbf{Z}} = Q(\overline{\mathbf{Z}}) = Q(\widetilde{\mathbf{H}}^{+}\mathbf{Y}). \quad (8)$$

Here, the quantization $Q(\cdot)$ corresponds to a rounding operation because the symbols in the lattice are integer elements. The estimated symbols are finally transformed from the original basis as follows

$$\widehat{\mathbf{X}} = \mathbf{T}\widehat{\mathbf{Z}} = \mathbf{TT}^{-1}\mathbf{X}. \quad (9)$$

To use lattice theory, the original constellation points consist of symbols in $\mathbb{Z}_{\mathbb{C}}$, where $\mathbb{Z}_{\mathbb{C}}$ is set of integers. However, general L-QAM (where L is constellation size) constellations neither consist of continuous integer nor contain the origin and thus it is necessary to scale and shift the original constellation [9]. For example, it is assumed that the shifted and scaled constellation symbols are transmitted in noiseless channel. The received signal vector is

$$\mathbf{Y}' = \mathbf{HX}' = \mathbf{H}\frac{1}{2}[\mathbf{X} + \mathbf{l}] = \frac{1}{2}\mathbf{Y} + \frac{1}{2}\mathbf{Hl}, \quad (10)$$

where $\mathbf{X}'$ is shifted and scaled for transmit symbols. Moreover, $\mathbf{X}$ is original symbols in $\mathbb{Z}_{\mathbb{C}}$. $\mathbf{l}$ is $2N_T \times 1$ vectors with $[1, \ldots, 1]^T$. It multiply the Moore-Penrose pseudo-inverse matrix of $\widetilde{\mathbf{H}}$ in Eq. (10) as follows

$$\mathbf{Z} = \frac{1}{2}\mathbf{H}^{+}[\mathbf{HT}(\mathbf{T}^{-1}\mathbf{X}) + \mathbf{HT}(\mathbf{T}^{-1}\mathbf{l})] = \mathbf{T}^{-1}\mathbf{X}'. \quad (11)$$

To transfer continuous integer, the $\mathbf{T}$ at $\mathbf{Z}$ is multiplied and then transmitted symbols $\mathbf{X}$ are as follows

$$\overline{\mathbf{X}} = 2\mathbf{T}Q(\mathbf{Z}) - \mathbf{l}. \quad (12)$$

4. Proposed Detection Scheme

In this section, the improved performance detection scheme for MIMO-OFDM system is proposed. The basic idea is that the received symbols through bad channel conditions are arranged in reverse order due to the performance of system considerably depending on detection capability of the first layer. Afterward, V probable symbols are detected at the first layer, and then rest layer is detected with complex LRD scheme. Afterward, among the decoded substreams, the most probable stream is selected by ML test. The whole algorithm is described as follows.

Because mean square error (MSE) is directly proportional to $\|\mathbf{G}\|^2$, the $\|\mathbf{g_j}\|^2$ is calculated and sorted from the smallest to the largest value. $\mathbf{g_j}$ is the j-th row of the $\mathbf{G}$ matrix. $\mathbf{G}$ is Moore-penrose Pseudo-inverse matrix and is determined as $\mathbf{G} = (\mathbf{H}^H\mathbf{H})^{-1}\mathbf{H}^H$. The sorted indexes are saved in sequence $\mathbf{k}$, $\mathbf{k} = [k_1 k_2 \cdots k_n]$. The columns of the channel matrix $\mathbf{H}$ from well-condition channels to ill-condition channels according to the sorted index sequence $\mathbf{k}$. Because the accurate detection of the first layer improves overall system performance, rearrangement of channel matrix is positively necessary.

Rearrangement channel matrix is performed by the QR decomposition, $\underline{\mathbf{H}} = \mathbf{QR}$, where $\mathbf{R}$ is an upper triangular matrix and $\mathbf{Q}$ is an orthonormal matrix satisfied with $\mathbf{Q}^H\mathbf{Q} = \mathbf{I}$. By multiplying $\mathbf{Q}^H$, the $N\times 1$ output vector can be expressed as $\mathbf{Z} = \mathbf{Q^H Y} = \mathbf{Q^H \underline{H} X} + \mathbf{Q^H N} = \mathbf{RX} + \tilde{\mathbf{N}}$.

$$\begin{bmatrix} z_1 \\ z_2 \\ \vdots \\ z_N \end{bmatrix} = \begin{bmatrix} r_{1,1} & r_{1,2} \cdots & r_{1,N} \\ 0 & r_{2,2} \cdots & r_{2,N} \\ \vdots & \vdots \quad \ddots & \vdots \\ 0 & 0 \quad \cdots & r_{N,N} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{bmatrix} + \begin{bmatrix} \tilde{n}_1 \\ \tilde{n}_2 \\ \vdots \\ \tilde{n}_N \end{bmatrix}. \tag{13}$$

The first layer calculates metric values for the first symbol as $\|z_N - r_{N,N}\times\widehat{x}_{candi}\|^2$, where $\widehat{x}_{candi}$ denotes all possible constellation symbol and metric value is saved in memory. Therefore, C times metric calculations are performed, where C is constellation size. Then, metric values are ordered from the lowest to the largest value and only the number of $V(V \in C)$ symbols, which have the smallest metric values, is retained as $\widehat{\mathbf{X}}_{candi} = [x_N^{(1)}, \cdots, x_N^{(v)}, \cdots, x_N^{(V)}]$ [10].

Before V probable streams are detected with the CLLL, it revises Eq. (13) as follows

$$\begin{bmatrix} \widehat{z}_1 \\ \widehat{z}_2 \\ \vdots \\ \widehat{z}_M \end{bmatrix} = \begin{bmatrix} r_{1,1} & r_{1,2} \cdots & r_{1,M} \\ 0 & r_{2,2} \cdots & r_{2,M} \\ \vdots & \vdots \quad \ddots & \vdots \\ 0 & 0 \quad \cdots & r_{M,M} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_M \end{bmatrix} + \begin{bmatrix} \tilde{n}_1 \\ \tilde{n}_2 \\ \vdots \\ \tilde{n}_M \end{bmatrix}, \tag{14}$$

where M is $N-1$, $\widehat{z}_k$ is $\widehat{z}_k = z_k - r_{N,N}\times x_N$(where $1 \le k \le N-1$). To detect rest symbols, complex LRD scheme executes V times. V stream is $\widehat{\mathbf{x}} = [\widehat{\mathbf{x}}_k^{(1)}, \cdots, \widehat{\mathbf{x}}_k^{(v)}, \ldots \widehat{\mathbf{x}}_k^{(V)}]$. The detected signal is rearranged according to the order of transmit antenna by using the index sequence $\mathbf{k}$, $\widetilde{\mathbf{x}} = [\widetilde{\mathbf{x}}_k^{(1)}, \cdots, \widetilde{\mathbf{x}}_k^{(v)}, \ldots \widetilde{\mathbf{x}}_k^{(V)}]$.

The likelihood test using V stream is performed. The likelihood test can be expressed as

$$P(\mathbf{Y}|\widetilde{\mathbf{X}}^{(v)}) = [(\mathbf{Y} - \mathbf{H}\widetilde{\mathbf{X}}^{(v)})^H(\mathbf{Y} - \mathbf{H}\widetilde{\mathbf{X}}^{(v)})]. \tag{15}$$

Table 1 Number of multiplication for each detection.

Detection Techniques	Required number of multiplication	$N = N_T = N_R = 4$	
Zero-Forcing	$12N^3 + 4N^2$	832	
Complex LR-aided Detection	$12N^3 + 8N^2 + 4N^3 + 669$	1821	
ML Detection	$4N^2C + 2NC^N$	525312	
QRD-M	$4N^3 + 4N^2 + 8C + \sum_{n=2}^{N}(4MCn + 4MC)$	$M = 16$	
		12736	
Proposed Scheme	$16N^3 + 8N^2 + 8C + 4VN + 16(N-1)^3$ $+4(N-1)^2(V+1) + 4VN^2 + 669$	$V = 12$	$V = 16$
		3809	4273

Table 2 The average complexity of the CLLL algorithm.

	The average complexity of the CLLL algorithm			
The number of Antennas	$N_T = N_R = 1$	$N_T = N_R = 2$	$N_T = N_R = 3$	$N_T = N_R = 4$
The average number of multiplications	0	80.39	295.23	669.24

Equation (15) is equivalent to minimum Euclidean distance. Thus, transmitted symbols are estimated as following method

$$\widetilde{\mathbf{X}}_{final} = \underset{\widetilde{\mathbf{x}}^{(v)}\in\widetilde{\mathbf{x}}}{\arg\min} \left\|\mathbf{Y} - \mathbf{H}\widetilde{\mathbf{X}}^{(v)}\right\|. \tag{16}$$

Because channel matrix was rearranged, performance has been improved considerably than conventional unordered scheme [10]. Table 1 shows number of multiplication for each detection and Table 2 shows the average complexity of the CLLL algorithm. The complexity of the proposed scheme can be reduced than QRD-M in Table 1. Therefore, proposed detection scheme with low complexity can be approached to QRD-M performance.

5. Simulation Results

In this section, the BER performance and the complexity of the proposed scheme are compared with other schemes as ZF, LRD and QRD-M. To evaluate the BER performance, the proposed detection scheme considers MIMO-OFDM system which the number of subcarriers is 64 and 16-QAM modulation. The channel model is Rayleigh fading channel model and channel path length is 7. Figure 1 shows the BER performance of proposed scheme with $V = 12$ and $V = 16$. The BER performance of QRD-M with $M = 16$ is also shown in Fig. 1. As expected, the proposed scheme has better performance than ZF and complex LRD scheme. ZF and complex LRD have low error performance due to incorrect symbol at the first layer. However, the proposed scheme has better error performance due to the adoption of ordered V candidate symbols at the first layer. Although complexity is increased due to the rearrangement of channel matrix, the performance of proposed scheme is improved than conventional unordered scheme about 3dB. Finally, the comparable error performance of QRD-M ($M = 16$) is acquired. Although the performance is degraded, the degradation value

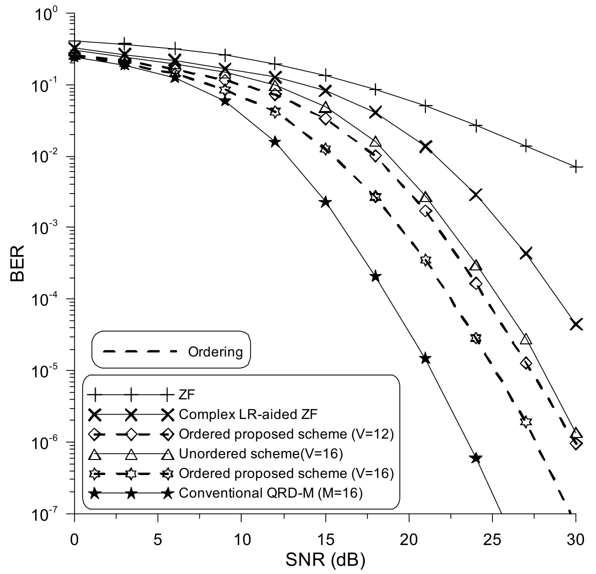

Fig. 1 BER performance of ZF, complex LRD, QRD-M and proposed scheme.

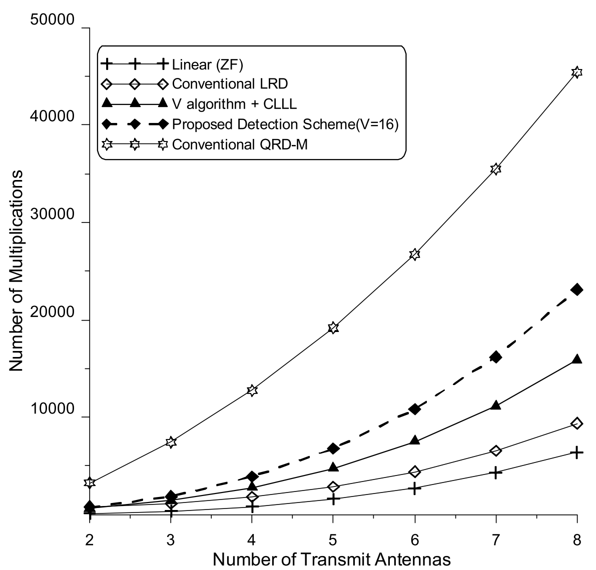

Fig. 2 Complexity of ZF, complex LRD, QRD-M and proposed scheme.

is not high. In case of $N_T = N_R = 4$ with $V = 16$, the performance degradation of the proposed detection is about 3dB compared with the QRD-M. Although there are some performance degradations, the complexity of proposed detection scheme can be reduced less than two thirds. If the first layer selects the suitable V value, complexity can be further reduced.

Figure 2 illustrates the computational complexity of the detection schemes in accordance with the nummber of antennas ($V = M = 16$). The complexity of QRD-M is highly increased by the number of transmit and receive antennas, constellation level and M level. The difference of each complexity between the proposed detection and the QRD-M is increased according to the number of antennas, and the complexity of proposed scheme is about 33.6% of the QRD-M with 4×4 MIMO system.

6. Conclusion

The performance of MIMO-OFDM system with LRD scheme is limited by the first detected symbol due to error propagation. For this problem, a novel detection scheme is proposed. The proposed detection scheme which can detect the first sub-stream more accurately has lower complexity than QRD-M. Simulation results show that the proposed detection scheme provides almost the same performance of QRD-M and the complexity of the proposed scheme is about two thirds of the complexity of QRD-M. Therefore, the proposed scheme can be effectively used for MIMO-OFDM receiver implementation requiring very low complexity.

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