Proceedings of ISAP'04, Sendai, JAPAN

SIMPLIFIED MLD ASSISTED BY PER-CANDIDATE ORDERED SUCCESSIVE DETECTION

Masaaki Fujii

Samsung Yokohama Research Institute Co., Ltd.
2-7 Sugasawa-cho, Tsurumi-ku, Yokohama, 230-0027, Japan
E-mail: fmasaaki@samsung.co.jp

1. Introduction

Multiple-input and multiple-output (MIMO) systems increase the capacity of wireless communication links in rich-scattering multipath environments. Among the several detection algorithms, ordered successive detection (OSD), which is known as V-BLAST [1], is a low-complexity iterative detection approach. However, OSD [2], [3] does not provide full diversity gain due to nulling out remaining sub-streams. In addition, decision errors cause error propagation to the subsequent stages.

On the other hand, maximum likelihood detection (MLD) is an optimum detection algorithm and it provides the best transmission performance [4]. MLD chooses the most likely signal vector out of all possible signal-vector combinations. Hence, its computational complexity increases exponentially with the number of transmit antennas and the number of constellation points.

In this paper, we propose using OSD to limit the number of symbol vector candidates. At the ***i***-th stage in OSD, the L_i closest symbol candidates from a decision variable are retained. Accordingly, OSD needs to be applied to multiple symbol candidates, a technique which we call "per-candidate OSD" in this paper. At the first detection stage, the L_1 closest symbol candidates are selected from an output signal of a spatial filter. Then L_1 replica signals are respectively subtracted from the received signal vector. Accordingly, L_1 residual received signal vectors are generated. At the second stage, the L_2 closest symbol candidates are selected from each output signal of the spatial filters for L_1 residual signal vectors. Accordingly, L_1L_2 symbol candidates are retained for the two sub-streams. At the final stage of per-candidate OSD, the number of symbol-vector candidates retained will be $L_1L_2\cdots L_{N_T}$ for all sub-streams. Thus, the number of symbol vector candidates is dramatically reduced. The subsequent MLD thus searches $L_1L_2\cdots L_{N_T}$ symbol-vector candidates to detect a symbol vector providing the minimum distance between the replica vector and received signal vector.

2. System Model

We consider a MIMO system with N_T transmit and N_R receive antennas. The number of modulation constellation points is M. The configuration of the detection algorithm is shown in Fig. 1.

A. Channel model

The received signal vector is given by

$$\boldsymbol{y} = \boldsymbol{H}\boldsymbol{s} + \boldsymbol{n}, \tag{1}$$

where $\boldsymbol{s} = [s_1, s_2, \cdots, s_{N_T}]^T$ denotes the N_T-dimensional transmit signal vector, $\boldsymbol{H}$ is an ($N_R \times N_T$) channel matrix, and $\boldsymbol{n}$ is a noise vector. The elements of $\boldsymbol{H}$ are assumed to be independent and identically distributed complex Gaussian random variables with zero-mean and unit-variance. Here the channel is assumed to be time-invariant during the packet.

B. Ordering and nulling matrices

In the first ordering step (i = 1), let $\boldsymbol{H}_1 = \boldsymbol{H}$. The nulling matrix is calculated by using zero-forcing (ZF) or minimum mean square error (MMSE) as

$$\boldsymbol{W}_i = \begin{cases} \left[\boldsymbol{H}_i^H \boldsymbol{H}_i\right]^{-1} \boldsymbol{H}_i^H & ZF \\ \left[\boldsymbol{H}_i^H \boldsymbol{H}_i + \sigma^2 \boldsymbol{I}\right]^{-1} \boldsymbol{H}_i^H & MMSE, \end{cases} \tag{2}$$

where the superscript H denotes the complex conjugate, σ^2 is the variance of the noise, and $\boldsymbol{I}$ is the

ISBN: 4-88552-206-4 C3055©IEICE

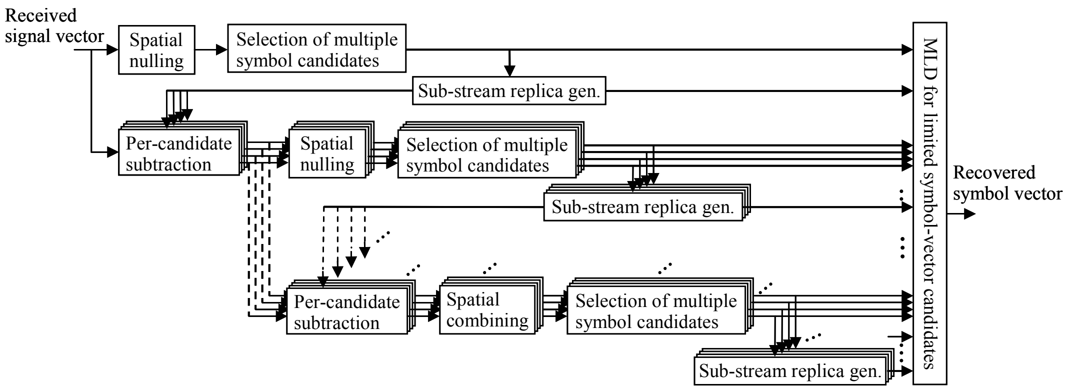

Fig. 1 Detection algorithm.

identity matrix. It is more trustworthy to start with the sub-stream providing the greatest post-detection signal-to-noise ratio (SNR). The sub-stream to be detected is found as

$$k_i = \arg \min_{j \in \{1, \cdots, N_T - i + 1\}} \left\| [\boldsymbol{W}_i]_j \right\|^2, \tag{3}$$

where $[\boldsymbol{W}]_k$ refers to the k-th row vector of $\boldsymbol{W}$. Within the channel matrix, the k_i-th column vector is no longer necessary and thus eliminated. This operation is expressed as

$$\boldsymbol{H}_{i+1} = \boldsymbol{H}_i^{(k_i)}, \tag{4}$$

where the matrix size of $\boldsymbol{H}_i$ is $N_R \times (N_T - i + 1)$. This procedure is repeated until all sub-streams are ordered: that is, $i = N_T$. We also obtain the order of detection, which is denoted as

$$D \equiv \{ k_1, k_2, \cdots, k_i, \cdots, k_{N_T} \}. \tag{5}$$

This order is used for all symbol time slots during a packet.

C. Per-candidate OSD

Let the number of multiple symbol candidates retained at the i-th stage be L_i, $(1 \le L_i \le M)$. The number of multiple symbol candidates for N_T sub-streams is thus denoted as

$$L \equiv \{ L_1, L_2, \cdots, L_i, \cdots, L_{N_T} \}. \tag{6}$$

Let the residual received signal vector at the i-th stage be $\boldsymbol{y}_i^{(l_1, l_2, \cdots, l_{i-1})}$ and be set at $\boldsymbol{y}$ at the first stage (i = 1). Thus, $\boldsymbol{y}_i^{(l_1, l_2, \cdots, l_{i-1})}$ is the residual received signal vector $\boldsymbol{y}_{i-1}^{(l_1, l_2, \cdots, l_{i-2})}$ at the (i-1)-th stage from which the l_{i-1}-th symbol selected at the (i-1)-th step is subtracted. Also, l_{i-1} corresponds to the index of symbol candidates selected in the (i-1)-th step and $l_i = 1, 2, \cdots, L_i$. Multiplying the nulling vector $[\boldsymbol{W}_i]_{k_i}$ with the residual received signal vector $\boldsymbol{y}_i^{(l_1, l_2, \cdots, l_{i-1})}$ suppresses all remaining sub-streams except the one transmitted from antenna k_i. A scalar decision variable is thus obtained as

$$z_i = [\boldsymbol{W}_i]_k \boldsymbol{y}_i^{(l_1, l_2, \cdots, l_{i-1})}. \tag{7}$$

Here, the L_i (≥ 1) closest symbols from the recovered signal point are selected as

$$\bar{\boldsymbol{s}}_i = Q(z_i), \tag{8}$$

where $Q(\cdot)$ denotes the operation of selecting the L_i closest symbols from the decision variable. The L_i symbol candidates are denoted as

$$\bar{\boldsymbol{s}}_i = \left[\tilde{s}_i^{(1)}, \tilde{s}_i^{(2)}, \cdots, \tilde{s}_i^{(l_i)}, \cdots, \tilde{s}_i^{(L_i)} \right]^T. \tag{9}$$

The L_i symbols selected at the i-th stage will be used in the subsequent MLD. Thus, L_i symbol candidates are added to the symbol candidates retained in the (i-1)-th step as

$$\begin{cases} \quad \vdots \\ \tilde{\boldsymbol{s}}(\cdots, l_{i-1}, 1) = \left[\, \cdots, \tilde{s}_{i-1}^{(l_{i-1})}, \tilde{s}_i^{(1)} \right]^T \\ \tilde{\boldsymbol{s}}(\cdots, l_{i-1}, l_i) = \left[\, \cdots, \tilde{s}_{i-1}^{(l_{i-1})}, \tilde{s}_i^{(2)} \right]^T \\ \quad \vdots \\ \tilde{\boldsymbol{s}}(\cdots, l_{i-1}, L_i) = \left[\, \cdots, \tilde{s}_{i-1}^{(l_{i-1})}, \tilde{s}_i^{(L_i)} \right]^T . \\ \quad \vdots \end{cases} \tag{10}$$

Next, L_i replica vectors for the interference (or the sub-stream) caused by $\tilde{s}_i^{(l_i)}$ are generated as

$$\boldsymbol{v}_i^{(l_i)} = (\boldsymbol{H}_i)_{k_i} \tilde{s}_i^{(l_i)} , \tag{11}$$

where $l_i = 1, 2, \cdots, L_i$ and $(\boldsymbol{H}_i)_{k_i}$ refers to the k_i-th column vector of $\boldsymbol{H}_i$. The signal candidates are cancelled from the residual received signal vector as

$$\boldsymbol{y}_{i+1}^{(l_1, l_2, \cdots, l_i)} = \boldsymbol{y}_i^{(l_1, l_2, \cdots, l_{i-1})} - \boldsymbol{v}_i^{(l_i)} . \tag{12}$$

At the same time, the replica signals for the sub-stream are accumulated to generate replica signals for the received signal vector $\boldsymbol{y}$ as

$$\boldsymbol{r}_i(\cdots, l_{i-1}, l_i) = \boldsymbol{r}_{i-1}(\cdots, l_{i-1}) + \boldsymbol{v}_i^{(l_i)} . \tag{13}$$

D. MLD using limited symbol-vector candidates

The symbol-vector candidates limited by per-candidate OSD are tested by using the constructed replica signals $\boldsymbol{r}_{N_T}(l_1, l_2, \cdots, l_{N_T})$ as

$$\hat{\boldsymbol{s}} = \arg \min_{l_i \in \{1, 2, \cdots, L_i\}} \left\| \boldsymbol{y} - \boldsymbol{r}_{N_T}(l_1, l_2, \cdots, l_{N_T}) \right\|^2 . \tag{14}$$

The detected signal vector $\hat{\boldsymbol{s}} = [\hat{s}_1, \hat{s}_2, \cdots, \hat{s}_{N_T}]^T$ is parallel-to-serial converted and then de-mapped into a bit sequence.

3. Computer Simulations

The bit error rate (BER) performance of the proposed scheme was evaluated by computer simulation. The simulation parameters are listed in Table I. The estimation of channels and noise variance is assumed to be perfect.

A. BER comparison of various schemes and the proposed scheme

Figures 2 and 3 show the BER performance of spatial filtering, OSD, MLD, and the proposed scheme with various quantities of multiple symbol candidates. Spatial filtering based on ZF or MMSE only provides one order (= N_R–N_T+1) of diversity gain. OSD based on ZF or MMSE improves the BER performance. However, the diversity order obtained in the sub-stream detected first is still one and the errors occurring in the sub-stream are dominant with respect to the overall errors. Therefore, the diversity order is not improved. In the proposed scheme based on ZF, the diversity order is not improved when L_1 is set at 4 or 8. This is because none of the multiple symbol candidates was the correct symbol at the first sub-stream detected. Thus, to improve the diversity order, L_1 needs to be set at 16 (= M). When the acceptable degradation from the BER achieved by MLD is 2 dB at 1.0×10^{-5}, L can be set at (16, 4, 1, 1). In this case, the number of limited symbol-vector candidates is 64. In the proposed scheme based on MMSE, the diversity order was improved when L_1 was set at 8. This is because the noise enhancement was mitigated because of MMSE and thus errors beyond the multiple symbol candidates at the first sub-stream detected were reduced. Therefore, L_1 can be set at 8. When the acceptable degradation from the BER achieved by MLD is 2 dB at 1.0×10^{-5}, L can be set at (8, 4, 1, 1). In this case, the number of limited symbol-vector candidates is 32.

B. Computational complexity

In this section, we consider the computational complexity of OSD, MLD, and the proposed scheme with, as an example, L = (8, 4, 1, 1), for the case of (4 × 4) MIMO with 16QAM. Table II lists the number of units for each function processed during one symbol time slot. In the proposed scheme, the computational complexity related to OSD increases, whereas that related to MLD is dramatically reduced. Therefore, the overall computational complexity is significantly reduced. However, the following should be noted. In MLD, the same replicas are used for all time slots. In contrast, in the proposed scheme, the limited replicas are not always the same for different time slots because the combinations of symbol candidates are different for the time slots.

4. Conclusions

We have proposed a simplified maximum likelihood detection (MLD) assisted by per-candidate ordered successive detection (OSD). Per-candidate OSD retains multiple symbol candidates for each sub-stream. MLD searches for the most likely transmitted signal vector among the limited symbol-vector candidates. Therefore, the number of multiple symbol candidates for each sub-stream can be set according to the acceptable degradation from MLD at a particular BER. Thus, the proposed scheme provides a good compromise between OSD and MLD.

References

[1] G. J. Foschini, "Layered space-time architecture for wireless communication in a fading environment when using multiple antennas," *Bell Laboratories Technical Journal*, vol. 1, no. 2, Autumn, 1996, pp. 41-59.

[2] A. Benjebbour and S. Yoshida, "Performance improvement of ordered successive detection with imperfect channel estimates for MIMO systems," *IEICE Trans. Commun.*, vol. E86-B, no. 11, pp. 3200-3208, November 2003.

[3] S. Baro, G. Bauch, A. Pavlic, and A. Semmler, "Improving BLAST performance using space-time block codes and Turbo decoding," *GLOBECOM'00*, San Francisco, pp. 1067-1071, November 2000.

[4] A. van Zelst, R. van Nee, and G. A. Awater, "Space division multiplexing (SDM) for OFDM systems," *VTC'00-Spring*, Tokyo, pp. 1070-1074, May 2000.

[5] H. Sung, K. B. Lee, and J. W. Kang, "A simplified maximum likelihood detection scheme for MIMO systems," *VTC'03-Fall*, Orlando, October 2003.

[6] T. Fujita, T. Onizawa, W. Jiang, D. Uchida, T. Sugiyama, and A. Ohta, "A new signal detection scheme combining ZF and K-best algorithms for OFDM/SDM", *Technical Report of IEICE*, RCS2003-266, pp. 133-138, January 2003.

TABLE I

SIMULATION PARAMETERS

Number of transmit antennas	$N_T = 4$
Number of receive antennas	$N_R = 4$
Modulation scheme	16 QAM
Number of constellation points	$M = 16$
Frame length	48 symbol time slots
Number of bits per frame	768

TABLE II

COMPUTATIONAL COMPLEXITY

Functions	OSD	MLD	Proposed scheme
Matrices calculation	3	–	3
Spatial filtering	4	–	73
Sub-stream replica gen.	3	64	56
Subtraction	3	–	72
Replica gen.	–	65536	32
Comparison	–	65535	31

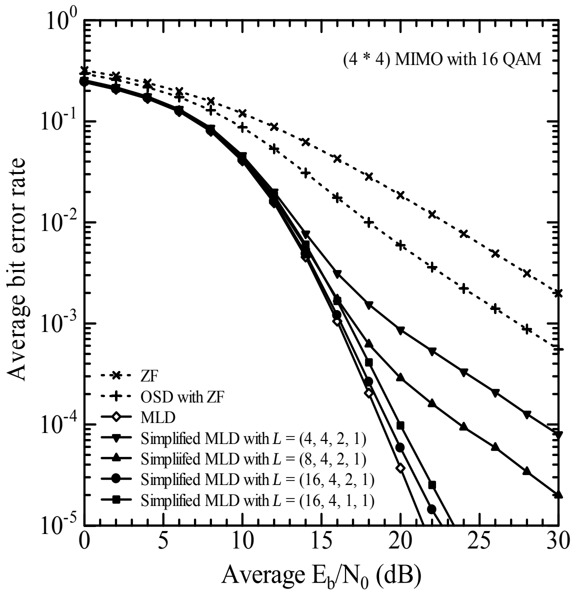

Fig. 2 Average BER comparison of various schemes based on ZF.

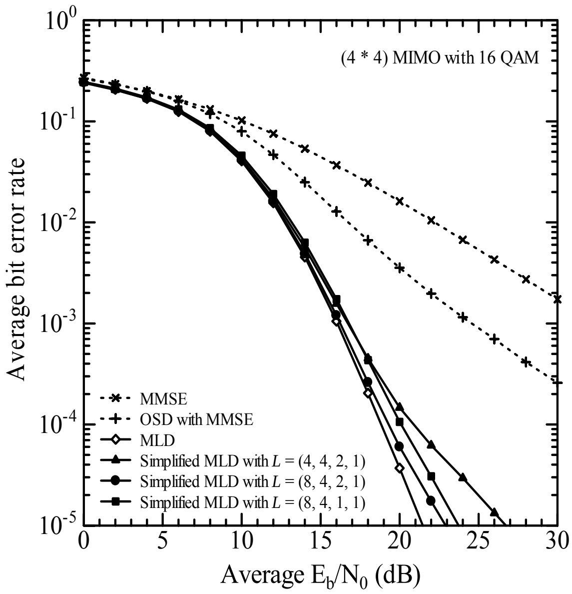

Fig. 3 Average BER comparison of various schemes based on MMSE.