SMLD: Enhanced MIMO-Signal Detection for Wireless MIMO Communication Receivers

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ABSTRACT—This letter proposes a simplified maximum likelihood detection (SMLD) scheme to improve the detection performance of multiple-input multiple-output receivers. The SMLD detects V streams according to the first detected V sub-streams. Through an ML test, the most probable stream is selected. Moreover, to detect the layer with the worst post-detection SNR accurately, reverse ordering is applied to the SMLD. Simulation results show that the performance of the Vertical Bell Laboratories layered space-time (V-BLAST) system can be improved by adopting the SMLD technique. In the case of reverse ordering, the SMLD can achieve a similar ML performance with significant reduction in computational complexity.

Keywords—SMLD, MIMO, ML, DFE, reverse ordering.

I. Introduction

The multiple-input multiple-output (MIMO) system called Vertical Bell Laboratories layered space-time (V-BLAST) is used for very high spectral efficiency [1]. Although a maximum likelihood (ML) detection scheme has the best detection performance among the existing detection schemes, the complexity of ML detection is excessively high. For practical implementation, a suboptimum scheme, sorted decision feedback equalization (DFE), or the ordered successive interference cancellation (OSIC) detection scheme is generally used [1], [2]. However, its performance is limited due to noise enhancement and error propagation. In OSIC or sorted DFE detection, since the detection accuracy of the first detected sub-stream influences the detection performance of all remaining sub-streams, the accurate detection of first layer is very important. Moreover, the sub-stream with the smallest post-detection SNR will dominate the error performance of the system [1]. In this letter, for more accurate detection of the initial layer, a simplified ML detection (SMLD) technique is proposed. For accurate detection of the worst sub-stream, a reverse ordering scheme is used.

II. System Description

We consider a V-BLAST system with N_t transmit antennas and N_r receive antennas. Because the symbols are transmitted from N_r transmit antennas in parallel, the $N_r \times 1$ data sequence matrix is $\mathbf{S} = [S_1 S_2 \cdots S_{N_t}]^T$.

The overall channel $\mathbf{H}$ can be represented as $N_r \times N_t$ complex matrix and the received baseband signal at the j-th receiving antenna is

$$Y_j = \sum_{i=1}^{N_t} H_{ji} S_i + w_j, \qquad (1)$$

where H_{ji} is the channel element with the i-th transmit antenna and the j-th receiving antenna, and w_j is the zero-mean Gaussian noise with variance σ_w^2.

III. SMLD Technique

The whole algorithm of SMLD is described as follows.

Step 1. Determine V sub-streams at the first detection using a sorted-DFE detector.

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In the sorted minimum mean square error (MMSE) QR decomposition, the $\| \mathbf{G}_{\text{MMSE}} \|^2$ is calculated and its elements are sorted from the smallest to the largest if $V \neq M$ or from the largest to the smallest (reverse ordering) if $V=M$, where $\mathbf{G}_{\text{MMSE}}=(\underline{\mathbf{H}}^{\text{H}}\underline{\mathbf{H}})^{-1}\underline{\mathbf{H}}^{\text{H}}$ and $\underline{\mathbf{H}} = \left[\mathbf{H};\ \sigma_w \mathbf{I}_{N_t} \right]$. The sorted indices are saved in sequence **k**, $\mathbf{k} = [k_1\, k_2 \cdots k_{N_t}]$. The columns of channel matrix $\underline{\mathbf{H}}$ are rearranged according to the sorted index sequence **k**. The QR decomposition of rearranged channel matrix $\underline{\mathbf{H}}_{\text{sort}}$ is executed: $\underline{\mathbf{H}}_{\text{sort}} = \mathbf{QR}$, where $\mathbf{Q}$ is an orthonormal matrix ($\mathbf{Q}^H\mathbf{Q} = \mathbf{I}$) and $\mathbf{R}$ is an upper triangular matrix. Using the nulling vector, the $N_t \times 1$ output vector can be expressed as

$$\mathbf{Z} = \mathbf{Q}^H \mathbf{Y} = \mathbf{RS} + \boldsymbol{\eta} = \begin{bmatrix} r_{1,1} & r_{1,2} & \cdots & r_{1,N_t} \\ 0 & r_{2,2} & \cdots & r_{2,N_t} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & r_{N,N_t} \end{bmatrix} \begin{bmatrix} S_{k_1} \\ S_{k_2} \\ \vdots \\ S_{k_{N_t}} \end{bmatrix} \begin{bmatrix} \eta_1 \\ \eta_2 \\ \vdots \\ \eta_{Nt} \end{bmatrix}, \quad (2)$$

where $\boldsymbol{\eta} = \mathbf{Q}^H \mathbf{w}$. The first detected sub-stream of (2) can be presented as

$$\widetilde{S}_{k_{N_t}} = Z_{N_t} / r_{N_t,N_t} = (r_{N_t,N_t} \cdot S_{k_{N_t}} + \eta_{N_t}) / r_{N_t,N_t}, \quad (3)$$

and V probable sub-streams are determined. It can be expressed as

$$\hat{\mathbf{S}}_{k_{N_t}} = Q^{(V)}(\widetilde{S}_{k_{N_t}}), \quad (4)$$

where $Q^{(V)}(K)$ is the decision function which determines V symbols of the M-QAM system by checking the Euclidean distance from K to each symbol, and $\hat{\mathbf{S}}_{k_{N_t}} = [\hat{S}^{(1)}_{k_{N_t}}, \cdots, \hat{S}^{(v)}_{k_{N_t}}, \cdots, \hat{S}^{(V)}_{k_{N_t}}]$, where $\hat{S}^{(v)}_{k_{N_t}}$ is the v-th estimated symbol whose Euclidean distance from $\widetilde{S}_{k_{N_t}}$ is the v-th.

Step 2. Determine V streams by using sorted-DFE detector according to detected V sub-streams of step 1.

$$\begin{aligned} \hat{S}^{(1)}_{k_{N_t-1}} &= Q[(Z_{N_t-1} - r_{2,N_t} \hat{S}^{(1)}_{k_{N_t}}] / r_{N_t-1,N_t-1}], \cdots \\ \hat{S}^{(1)}_{k_1} &= Q[(Z_1 - \sum_{i=2}^{N_t} r_{1,i} \hat{S}^{(1)}_{k_1}) / r_{1,1}], \cdots \\ \hat{S}^{(V)}_{k_{N_t-1}} &= Q[(Z_{N_t-1} - r_{2,N_t} \hat{S}^{(V)}_{k_{N_t}}] / r_{N_t-1,N_t-1}], \cdots \\ \hat{S}^{(V)}_{k_1} &= Q[(Z_1 - \sum_{i=2}^{N_t} r_{1,i} \hat{S}^{(V)}_{k_1}) / r_{1,1}]. \end{aligned} \quad (5)$$

All the detected signals $\hat{\mathbf{S}} = [\hat{\mathbf{S}}^{(1)}, \cdots, \hat{\mathbf{S}}^{(V)}]$ are rearranged according to the order of the transmit antenna by using index sequence **k**, where $\hat{\mathbf{S}} = [\hat{S}^{(v)}_{k_1}\, \hat{S}^{(v)}_{k_2} \cdots \hat{S}^{(v)}_{k_{N_t}}]$.

Step 3. Select the most probable stream among V streams in step 2.

In this step, the final stream maximizing the likelihood is selected among V streams from the second step. Maximizing the likelihood function is equivalent to minimizing the Euclidean distance between $\mathbf{Y}$ and $\mathbf{H} \cdot \hat{\mathbf{S}}^{(v)}$. Thus, the final decision value can be obtained as

$$\hat{\mathbf{S}}_{\text{final}} = \arg \min_{\hat{\mathbf{S}}^{(v)}} \| \mathbf{Y} - \mathbf{H} \cdot \hat{\mathbf{S}}^{(v)} \|. \quad (6)$$

In the SMLD with $V = M$, since all M symbols are considered for probable V symbols, through reverse ordering we can detect the sub-stream with the smallest post-detection SNR very accurately and increase the system performance. In reverse ordering, the sorting process is executed reversely. Therefore, the index sequence $\mathbf{k}_{\text{R}} = [k_{N_t} k_{N_t-1} \cdots k_1]$ has the reverse combination of elements of forward ordering. The columns of channel matrix $\mathbf{H}$ are rearranged according to index sequence $\mathbf{k}_{\text{R}}$. After reverse ordering, the proposed detection is executed.

IV. Complexity Comparison

For computational complexity comparison, we consider the existing QRM-MLD scheme [5] which is a MIMO signal detection scheme based on QR decomposition. In this section, we consider only multiplications in the case $N_t = N_r$.

The complexity of each scheme is shown in Table 1. Figure 1 shows the number of multiplications of each decoding scheme. Since the QRM-MLD requires computations of branch metrics and path metrics at each detection step, the complexity is much higher than that of the SMLD technique.

V. Simulation Results

For the simulation, we consider the V-BLAST system with 16-QAM in a Rayleigh fading channel model with one path.

Figure 2 shows the BER performance of the SMLD with $N_t = N_r = 3$. As expected, the higher the number of V adopted, the better the BER performance achieved. In the case of $V = 16$, since all M symbols are considered for V candidate symbols,

Table 1. Number of multiplications for each decoding scheme.

Detection techniques	Required number of multiplications
SMLD	$4N_t^3 + 4N_t^2 + 1 + V\sum_{m=2}^{N_t} m + VN_t^2$
QRM-MLD	$4N_t^2 + 4N_t^2 + 4(N_t(N_t+1)/2)M + 2(1 + \sum_{m=1}^{N_t-1} S_m)M$
OSIC	$(43/12)N_t^4 + (22/3)N_t^3 + N_t^2 + N_t$
ML	$4N_t^2 M + 2N_t M^{M_t}$

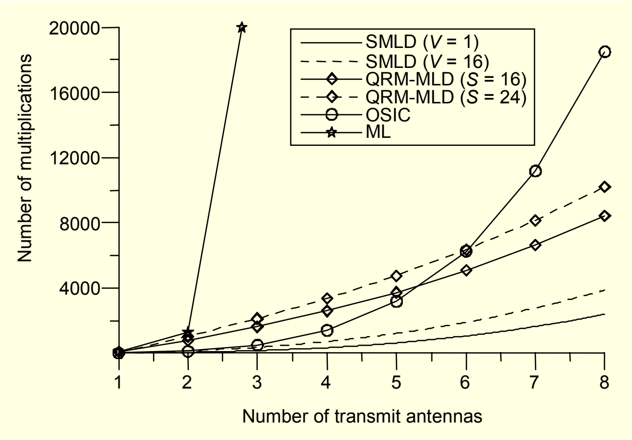

Fig. 1. Number of multiplications for each decoding scheme according to the number of transmit antennas.

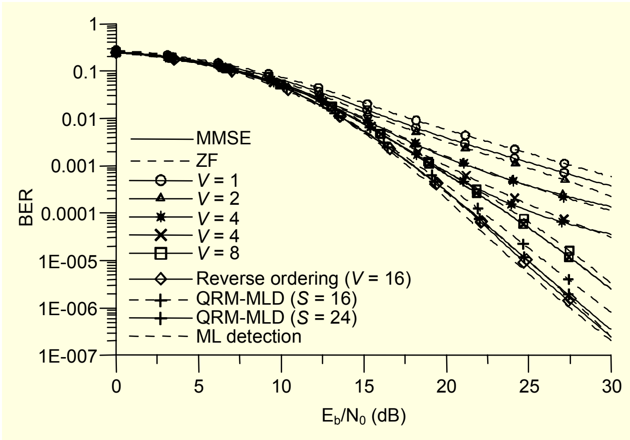

Fig. 2. BER performance of the proposed technique with $N_t = N_r = 3$ according to the number of V.

the MMSE and zero-forcing (ZF) detectors show similar performance. And since the MMSE detector can suppress error propagation efficiently, the detectors with both $V = 8$ and $V = 16$ show the same performance. In the case of reverse ordering, the performance of SMLD is very similar to that of the ML detector due to the accurate detection of the worst sub-stream. In the case of QRM-MLD, the SMLD technique with reverse ordering shows better performance and lower complexity than that of QRM-MLD.

Figure 3 illustrates the effect of the number of transmit antennas on the BER performance of the SMLD technique at an SNR of 25 dB. In the case of forward ordered MMSE detectors with V=4 and 16, we can find the floor phenomenon of the BER performance according to the increase of N_t, since many symbols have to be detected according to only one symbol. Therefore, the gain of the SMLD is reduced as N_t increases. In the case of SMLD with reverse ordering, the gain reduction is much higher than that of SMLD with forward ordering, because the error propagation and noise enhancement cannot be minimized. Therefore, the performance of SMLD with reverse ordering in $N_t > 5$ greatly decreases as N_t increases. However, in the case of $N_t \leq 4$, the performance increase of the SMLD with reverse ordering is very high, since the detector can detect the worst sub-stream accurately and the noise enhancement and error propagation are not high.

VI. Conclusion

Since the performance of the ordered V-BLAST system is limited by the first detected sub-stream due to error propagation, we proposed an SMLD technique. Simulation results show that the performance of the V-BLAST system can be improved by adopting the SMLD technique, and the decoding complexity and system performance can be controlled by adjusting the number of V.

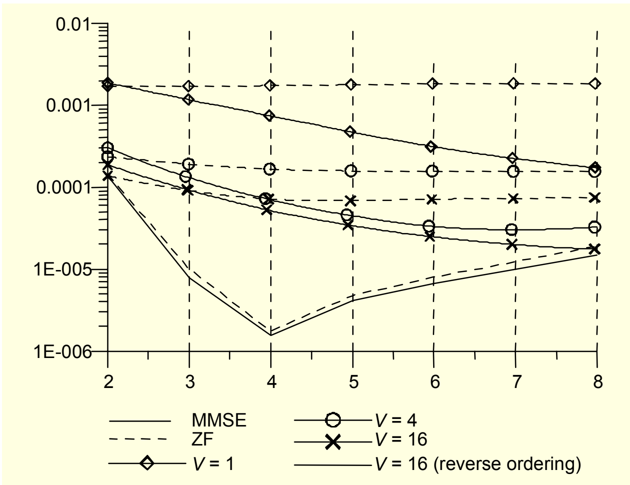

Fig. 3. BER performance according to the number of transmit antennas for SMLD at an SNR of 25 dB.

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