Joint OSIC and Soft ML Decoding Scheme for Coded Layered Space-Time OFDM Systems

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ABSTRACT

In this paper, we consider coded layered space-time architecture in MIMO-OFDM channels. Vertical Bell Lab Layered Space-Time (V-BLAST) scheme employing ordered successive interference cancellation (OSIC) algorithm provides very high spectral efficiency with low computational complexity. However, the error propagation is a major drawback constraining the overall performance of the V-BLAST system significantly. Based on this problem, we derive an improved detector using soft bit log-likelihood ratio (LLR) value. Simulation results show that the proposed detector outperforms the conventional V-BLAST scheme under spatially uncorrelated as well as correlated fading channels.

Key Words : OSIC, ML, V-BLAST, MIMO-OFDM

Ⅰ. Introduction

With the demand on wireless communication ever growing, the requirements of service with higher data rate and channel capacity are increasing. With this tendency, multiple-input multiple-output (MIMO) system is one of the most promising wireless technologies capable of providing high spectral efficiency and improving link quality using multiple antennas without expanding bandwidth or increasing transmit power[1]. Among MIMO technologies, spatial division multiplexing (SDM) is a throughput oriented technique where independent data streams are transmitted over different antennas, thus maximizing the average data rate over the MIMO system. Capacity can grow linearly with the number of transmit antennas in a rich scattering channel environment. One such practical signaling scheme has been originally proposed by Foschini and it is called V-BLAST. The V-BLAST consists of a combination of linear and nonlinear detection schemes such as minimum mean-squared-error (MMSE)-OSIC [2]: sequential nulling and canceling. V-BLAST first detects the strongest signal, cancels out the effect of this strongest transmit signal from the received signals, and then proceeds to detect the next strongest transmitted signal, and so on.

Orthogonal frequency division multiplexing (OFDM) is commonly used for high data rate wireless communication. Multicarrier modulation realized by OFDM is well suited for broadband applications[3]. A combination of MIMO with OFDM is regarded as a promising solution for enhancing the performance of wireless communication systems. The OFDM based transmission systems can be extended to MIMO architecture using V-BLAST.

The performance of V-BLAST employing OSIC is known to have limitations due to error propagation in decision feedback process. Various schemes have been investigated, however, most detectors achieve improved performance at the expense of highly increased computational complexity[4],[5]. The performance of OSIC is seriously affected by the last layer in which symbol detection may be erroneous due to

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논문번호 : KICS2006-07-324, 접수일자 : 2006년 7월 24일, 최종논문접수일자 : 2008년 5월 21일

accumulated interferences from previous layers. To improve performance effectively, it is necessary to increase the symbol correctness at the last layer.

In this paper, we propose an enhanced OSIC detector employing soft ML decoding. The ML scheme is an optimal detection scheme from the viewpoint of error rate and chooses the constellation point which maximizes likelihood function. The proposed scheme employs the optimal ML detection partially for the last layer and its computational complexity is reasonable. We also consider bit interleaved coded modulation (BICM) and soft-decision Viterbi decoding in the space-time OFDM system. By soft bit LLR value computation, soft bits as a soft de-mapped ML output are feed to the Viterbi decoder. The bit error rate (BER) of the proposed detector is evaluated by simulation and compared with that of conventional V-BLAST in uncorrelated and correlated fading channels. The rest of the paper is organized as follows: In section Ⅱ, the system model is described. In Section Ⅲ, the proposed detection scheme is described. Simulation results are given in Section IV and conclusions are drawn in Section Ⅴ.

Ⅱ. System Model

We consider a coded layered space-time OFDM system with N transmit antennas and M receive antennas. The transmitter structure is shown in Fig. 1.

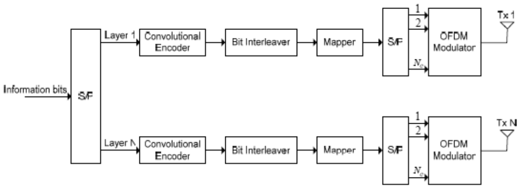

Fig. 1. Transmitter structure.

The information bits are de-multiplexed into N independent substreams, so called layers. Input bits of each layer are convolutionally encoded, bit-by-bit interleaved, and converted into symbols according to Gray mapping: BICM. The complex symbols are fed to OFDM modulator with N_C subcarriers. The received signal vector at the kth subcarrier is given by

$$r_k = H_k x_k + n_k \tag{1}$$

where $r_k = [r_{1,k}, r_{2,k}, \cdots, r_{M,k}]^T$ is the $M \times 1$received signal vector, $x_k = [x_{1,k}, x_{2,k}, \cdots, x_{N,k}]^T$ is the $N \times 1$ transmit symbol vector, $n_k = [n_{1,k}, n_{2,k}, \cdots, n_{M,k}]^T$ is the $M \times 1$ additive white complex Gaussian noise (AWGN) vector of which elements have zero mean and variance of σ^2. If $C = 2^{2G}$ is the number of symbols of QAM, G interleaved bits are mapped into the in-phase and quadrature-phase components of the transmit symbol. $\{b_{I,1}, b_{I,g}, \cdots, b_{I,G}, b_{Q,1}, b_{Q,g}, \cdots, b_{Q,G}\}$ is the corresponding bit sequence of $x_{n,k} = x_{I,n,k} + jx_{Q,n,k}$.

The correlated MIMO channel matrix for the kth subcarrier $\boldsymbol{H_k}$ is given by

$$\begin{aligned} H_k &= H_{R,k}^{1/2} H_{i.i.d,k} H_{T,k}^{1/2} \\ &= \begin{bmatrix} h_{1,1,k} & h_{1,2,k} & \cdots & h_{1,N,k} \\ h_{2,1,k} & \ddots & & h_{2,N,k} \\ \vdots & & \ddots & \vdots \\ h_{M,1,k} & h_{M,2,k} & \cdots & h_{M,N,k} \end{bmatrix} \end{aligned} \tag{2}$$

where

$$H_{R,k} = H_{T,k} = \begin{bmatrix} 1 & \rho & \rho^2 & \rho^4 \\ \rho & 1 & \rho & \rho^2 \\ \rho^2 & \rho & 1 & \rho \\ \rho^4 & \rho^2 & \rho & 1 \end{bmatrix} \tag{3}$$

The correlation matrices for the transmitter and receiver, $\boldsymbol{H_{T,k}}$ and $\boldsymbol{H_{R,k}}$, are expressed in the form of toeplitz matrix in case of $N = M = 4$ where ρ denotes correlation coefficient ranging 0 to 1. If $\rho = 0$, spatially uncorrelated MIMO channels can be obtained, i.e., $\boldsymbol{H_k} = \boldsymbol{H_{i.i.d,k}}$.. If Rician fading channels are considered, channel matrix can be modeled as

$$\tilde{\mathbf{H}}_k = \sqrt{\frac{K}{1+K}}\bar{\mathbf{H}}_k + \sqrt{\frac{1}{1+K}}\mathbf{H}_k. \tag{4}$$

where K is known as the Rician factor, $\overline{H_k}$ is the mean of $\widetilde{H_k}$ corresponding to the line-of-sight (LOS) component. Every element in $\widetilde{H_k}$ is an independent complex Gaussian random variable of non-zero mean and unit variance. Their amplitudes thus follow the Rician distribution. In case of $K=0$, the Rayleigh fading channels without LOS component are realized, i.e., $\widetilde{H_k}=H_k$.. If K approaches an infinite value, only LOS channel components are formed, i.e., $\lim_{K\to\infty}\widetilde{H_k}=\overline{H_k}$.

Ⅲ. Proposed Detection Scheme

Fig. 2 shows the block diagram of the proposed receiver structure.

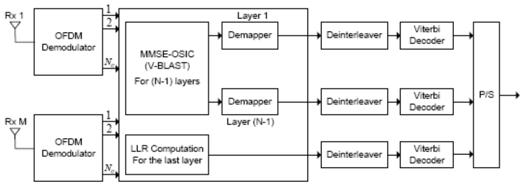

Fig. 2. Proposed receiver structure.

After OFDM demodulation, V-BLAST algorithm is operated for $(N-1)$ layers except the last layerand soft-decision values are passed to the de-mapper. For the last layer, soft output de-mapped value is obtained by bit-level LLR computation. We introduce the original V-BLAST and the proposed joint OSIC and soft ML decoding algorithm as follows.

3.1 Original V-BLAST algorithm

The V-BLAST processor as shown in Fig. 2 consists of linear MMSE and nonlinear OSIC algorithm. The V-BLAST operation for the kth subcarrier is described as follows.

For i=1 to N

$$\mathbf{W}_i=\mathbf{H}_i(\mathbf{H}_i^{\mathrm{H}}\mathbf{H}_i+\sigma^2\mathbf{I}_N)^{-1} \tag{5a}$$

$$m_i=\underset{j\in\{1,\dots,n-i\}}{\arg\min}\ \left\|(\mathbf{W}_i)_j\right\|^2 \tag{5b}$$

$$\hat{\mathbf{y}}_{m_i}=\mathbf{w}_{m_i}^{\mathrm{H}}\mathbf{r}_i \tag{5c}$$

$$\hat{\mathbf{x}}_{m_i}=Q(\hat{\mathbf{y}}_{m_i}) \tag{5d}$$

$$\mathbf{r}_{i+1}=\mathbf{r}_i-\mathbf{h}_{m_i}\hat{\mathbf{x}}_{m_i} \tag{5e}$$

$$\mathbf{H}_{i+1}=\mathbf{H}_{i\setminus\{m_i\}} \tag{5f}$$

End

In the above detection procedure, Equation (5a) denotes MMSE weight matrix, $W_{i,k}$ which is obtained by computing the Moore-Penrose pseudo-inverse of the channel matrix $H_{i,k}$ where $(\bullet)^H$ denotes the Hermitian operation, and I_N stands for the $N\times N$ identity matrix. If noise term is removed from (5a), it will reduce to Zero-Forcing (ZF) based pseudo-inverse matrix. Equation (5b) describes the optimal ordering operation to choose the layer with strongest signal-to-interference and noise ratio (SINR) to detect. Equation (5c) denotes the operation of nulling all the transmitted symbols except the m_i th symbol. Soft-decision value $\widehat{y_{m_i}}$ will be fed to the soft output de-mapper, de-interleaver and binary soft input Viterbi decoder after V-BLAST operation. Equation (5d) shows the quantization process in order to obtain the data estimation of the current layer by applying to the signal constellation. Interference cancellation operation is denoted in (5e). After each interference cancellation, the number of layers to be nulled in the next step is reduced by one which is equivalent to reducing the number of transmit antennas by one while maintaining the number of receive antennas, and this operation is expressed in (5f).

OSIC algorithm is a type of Decision Feedback Equalization (DFE) detection scheme which has a critical inherent drawback, error-propagation. If a symbol is detected erroneously in the DFE type detector, the error will be propagated into the next layers through the operation of interference cancellation. Consequently, last layer will have the accumulated errors from the previous layers and this causes the overall performance of the V-BLAST system to be degraded. As a requirement for improving performance of V-BLAST, correctness of symbol detection at the last layer is critical since the last layer is significantly impacted by accumulated errors. With this motivation mentioned above, we propose an enhanced detection algorithm as follows.

3.2 Proposed joint OSIC and soft ML decoding algorithm

The basic idea of the proposed algorithm is to employ ML criterion partially for the OSIC algorithm.

Step 1: Apply original V-BLAST algorithm in (5a~5f) for the number of $(N-1)$ iteration except the last layer.

Step 2: Apply the ML criterion for the last layer. After step 1, remaining received signal, $r_{N,k}$, is demodulated by soft output de-mapper, de-interleaved, and passed to a binary soft input Viterbi decoder. The system is equivalent to a single-input multiple-output (SIMO) channel with $N=1$ transmit and M receive antenna since only one layer remains to be detected after V-BLAST completed at Step 1. For the soft de-mapping, it is necessary to compute soft bit LLR value[6]. The LLR is defined as

$$LLR(b_{I,g}) = \log\frac{P[b_{I,g}=1|\boldsymbol{r_{N,k}}]}{P[b_{I,g}=0|\boldsymbol{r_{N,k}}]} = \log\frac{\sum_{\alpha\in S_{Ig}^{(1)}} P[x_{N,k}=\alpha|\boldsymbol{r_{N,k}}]}{\sum_{\alpha\in S_{Ig}^{(0)}} P[x_{N,k}=\alpha|\boldsymbol{r_{N,k}}]} \tag{6}$$

The equation (6) is the soft bit information assigned to bit $b_{I,g}$. The same LLR equation applies to $b_{Q,g}$. $S_{I,g}^{(1)}$ represents symbol set comprising the symbols with a '1' in position (I,g) and $S_{I,g}^{(0)}$ represents symbol set which is complementary. By applying Bayes' theorem and assuming that the transmitted symbols are equally distributed, equation (6) can be modified as

$$LLR(b_{I,g}) = \log\frac{\sum_{\alpha\in S_{Ig}^{(1)}} P[r_{N,k}|x_{N,k}=\alpha]}{\sum_{\alpha\in S_{Ig}^{(0)}} P[r_{N,k}|x_{N,k}=\alpha]} \tag{7}$$

Sub-optimal simplified LLR can be obtained by the log-sum approximation, $\log\sum_j(\cdot) \approx \max_j \log(\cdot)$, which the sum in the left-hand side is dominated by the largest term, as typically occurs in channels with high signal-to-noise ratio (SNR). Approximated LLR value can be expressed as

$$LLR(b_{I,g}) = \log\frac{\max_{\alpha\in S_{Ig}^{(1)}} P[r_{N,k}|x_{N,k}=\alpha]}{\max_{\alpha\in S_{Ig}^{(0)}} P[r_{N,k}|x_{N,k}=\alpha]} \tag{8}$$

Fig. 3 shows the partitions $(S_{I,g}^{(0)}, S_{I,g}^{(1)})$ for the bit $b_{I,g}$ and $(S_{Q,g}^{(0)}, S_{Q,g}^{(1)})$ for the bit $b_{Q,g}$ in case of the 16QAM constellation. For visualization, we provide the whole flow diagram of the proposed scheme in Fig. 4.

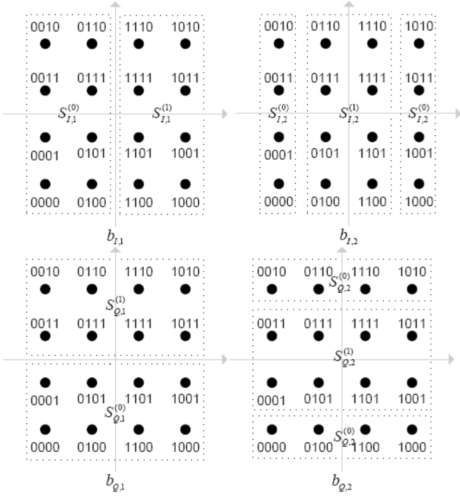

Fig. 3. Partitions of the 16QAM constellation.

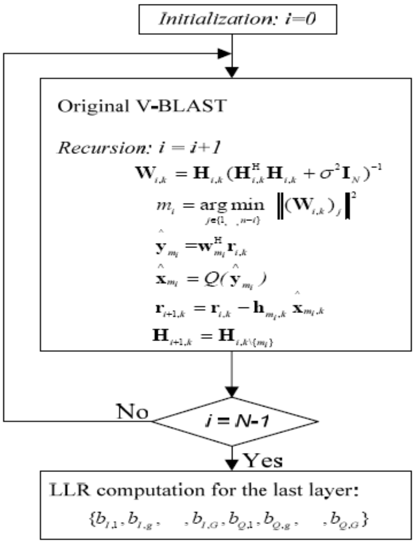

Fig. 4. Flow Chart of the proposed scheme.

3.3 Computational Complexity

In this section, a computational complexity is considered for the kth subcarrier. We consider only multiplication operation for the comparison. The total number of the multiplication for the V-BLAST scheme with MMSE nulling is obtained as[7]

$$M^3(N+1)+M((3/2)N^2+(7/2)N-1)-1 \quad (9)$$

In case of LLR computation, the total number of multiplication is $2MN^2C^N\log_2 C$ where C is the number of symbols in constellation, e.g., 4 for QPSK and 16 for 16QAM. As the LLR computation is applied to the V-BLAST scheme by layer, the computational complexity increases dramatically compared to performance. By considering trade-off between complexity and performance, the proposed scheme uses LLR value for the last layer, i.e., $N=1$. Table 1 shows the computational complexity comparison for QPSK and 16QAM when the number of antennas is four.

According to the Table 1, in case of QPSK modulation, the computational complexity of the proposed detector is about 1.1 times of that of V-BLAST scheme whereas about two times of complexity is required in case of 16QAM. However, the complexity of the proposed detector is only 0.8% of that of LLR computation. Compared with LLR complexity, our proposed algorithm provides remarkable benefits of reduced hardware complexity as calculated in Table 1.

Table 1. Computational complexity for $N=M=4$.

Modulation	V-BLAST	Proposed Detector	LLR
QPSK	467	531	65,536
16QAM	467	979	131,072

Ⅳ. Simulation Results

We consider coded layered space-time OFDM system with four transmit/receive antennas. In mobile communication standards such as 3GPP release 7 and IEEE 802.16e, maximum number of the transmitter and receiver antennas is four. Through simulation results with four antennas, we can estimate performance increasement margin. Suppose that the number of subcarriers is 64. Among them, 48 subcarriers are used for information data which is mapped to 16QAM. Convolutional coding with constraint length 7 is considered. We assume a perfect channel estimation and synchronization at the receiver.

Fig. 5 shows the bit error rate (BER) performance in uncorrelated Rayleigh fading channels with 1/2 and 3/4 coding rates. At the BER of 10^{-4}, the proposed detector's performance is improved by 2dB and 3dB compared with conventional MMSE-OSIC detector for coding rate 1/2 and 3/4, respectively. A significant performance gain is achieved about 4dB at the BER of 10^{-5}.

Fig. 6 shows the BER in uncorrelated Rician fading channels with 1/2 coding rate. $K=0$ means no LOS paths in MIMO channels. As Rician factor K increases, the channels become dominated by the stronger LOS path. It is observed that LOS channel factor causes severe degradation in the spatial multiplexing gain. MIMO systems show the best performance in rich scattering channels. In LOS dominant environments, channel correlation between antennas becomes higher and spatial multiplexing gain would be reduced.

Fig. 7 shows the BER performance curves with varying antenna correlations in correlated Rayleigh fading channels when average SNR is 20dB. $\rho=0$ means i.i.d MIMO channels as shown in equation (3). As ρ value increases toward 1, the MIMO channels are getting correlated. It is shown that the proposed algorithm has comparable tolerance to the spatial correlation with conventional MMSE-OSIC detector. As the correlation value decreases, performance increase of the proposed scheme is significant.

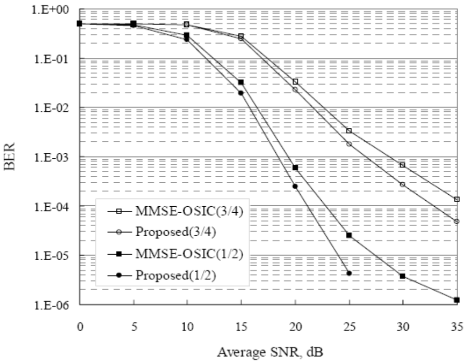

Fig. 5. BER performance in uncorrelated Rayleigh fading channels when coding rates are 1/2 and 3/4.

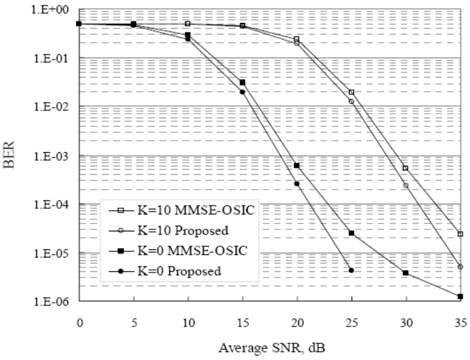

Fig. 6. BER performance in uncorrelated Rician fading channels when coding rate is 1/2.

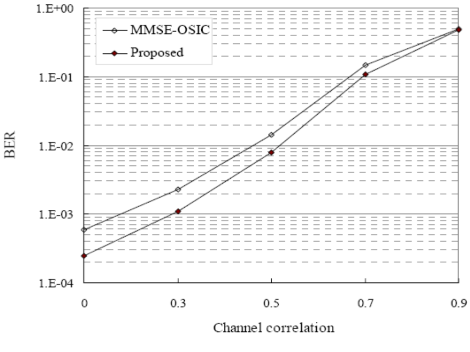

Fig. 7. BER performance in correlated Rayleigh fading channels (average SNR=20dB, 16QAM).

V. Conclusions

In this paper, joint OSIC and soft ML decoding scheme is proposed for coded layered space-time OFDM system. The proposed scheme performs soft bit LLR computation for the last layer to mitigate error propagation effect in OSIC algorithm. The performance of proposed detection scheme is evaluated for the space-time OFDM system with four transmit/receive antennas in uncorrelated and correlated fading channels. LOS path component affects the spatial multiplexing gain in uncorrelated Rician fading channels. However, it is shown that the proposed scheme has better performance than conventional OSIC detection with a reasonable increase of computational complexity in Rayleigh fading channels.

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