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대용량 다중안테나 시스템에 대한 저 복잡도 반복 SIC-MMSE 검출 기법

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Low-Complexity Iterative SIC-MMSE Detection for Massive MIMO Systems

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요 약

본 논문에서는 수신안테나의 수가 송신 안테나의 수보다 더 많은 대용량 안테나 시스템에 효율적으로 적용할 수 있는 연판정 기반 반복 검출 기법을 제안하였다. 제안된 기법에서는 최소평균자승오류(minimum mean squared error; MMSE) 기반의 검출 기법에서 가장 큰 연산량이 소요되는 복소 역행렬 연산을 뉴먼(Neumann) 무한급수 중 일부 중요 항을 채택함으로서 복잡도를 감소시킬 수 있도록 하였다. 본 논문에서는 이와 같은 복잡도 감소 기법이 부호화된 다중안테나 시스템에서 3개의 다중루프를 활용한 연판정 검출 기법에 적용될 수 있도록 하였으며, 대용량 안테나의 채널 특성을 활용하여 효율적으로 복잡도가 감소될 수 있도록 하였다. 본 논문에서 제시된 시뮬레이션 결과를 통하여 제안된 기법은 기존의 기법에 비하여 훨씬 더 적은 수의 연산량을 가지고도 기존 기법에 근사하는 성능을 도출할 수 있음을 확인하였다.

Key Words : Massive MIMO, soft detection, MMSE detection

ABSTRACT

This paper proposes an efficient soft iterative detection technique for massive multi-input multi-output systems, where the number of receive antennas is greater than that of transmit antennas. The proposed technique adopts minimum mean squared error (MMSE) based detection schemes, and the computational complexity is reduced by replacing the complex matrix inverse operation with a few dominant terms of the Neumann series. This paper presented a method to tailor this complexity reduction technique to a three-loop joint iterative detection for a coded massive MIMO system, and the complexity is efficiently reduced by using the channel characteristics of massive MIMO systems. The simulation results demonstrated in this paper reveal that the proposed method provides approximating performance to the conventional scheme with much less computational complexity.

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Ⅰ. Introduction

Recently, multiple-input multiple-output (MIMO) technologies have been widely studied as important schemes in most modern wireless communication systems. The advantage of utilizing multiple antennas which is called diversity gain is increased as the number of antennas is increased. The MIMO system with a very large number of antennas is called massive MIMO system or large-scale MIMO system. As the number of antennas is increased, we have more serious interference problem during the signal detection process at the receiver. For this reason, we generally assume that the number of receive antennas is larger than that of transmit antennas in massive MIMO systems.

In massive MIMO systems, the forward error correction (FEC) or channel coding is also an important part to exploit the full diversity gain from the multi antennas. With longer codeword lengths and iterative decoding process, the advantage of utilizing FEC can be approached to the capacity limiting bit error rate (BER) performance. When an iterative channel decoder is employed in MIMO systems, the iterative principle can be extended to the symbol-level detector as an outer loop. This outer loop is able to feedback soft-input and soft-output (SISO) information from iterative decoder to detector[1]. This kind of detection scheme with outer loop is called joint iterative detection and decoding (JIDD) schemes. By adding another self-iterative loop inside of the MIMO detector, JIDD system with three loops were presented[2,3].

These conventional JIDD schemes utilized soft interference cancellation-minimum mean squared error (SIC-MMSE) detection methods for MIMO systems with moderate number of antennas less than eight. Since the conventional MMSE filtering based detection requires layer by layer matrix inversion processes, a single matrix inversion based scheme was applied in order to reduce the complexity[3]. Nevertheless, the three-loop JIDD scheme is too complex to be applied to massive MIMO system with a few tens of antennas. For a massive MIMO system, a number of complexity reduced detection schemes were proposed by eliminating matrix inversion process during the MMSE detection process, by considering that the critical computational burdens of the MMSE detection process lies in the complex matrix inversion process[4-7]. These methods utilized the fact that the filtering matrix used in the MMSE process could be approximated as a diagonal matrix.

In this paper, we propose a modified SIC-MMSE detection schemes with three loops, which is specially tailored for massive MIMO system. The proposed method utilizes the Neumann series expansion (NSE) method[4], and it achieves complexity reduction by eliminating matrix inversion processes during the SIC-MMSE filtering processes. We apply the NSE to the filtering matrix for a massive MIMO system, and eliminate the complex matrix inversion process during the detection process. The simulation results for massive MIMO systems show that the performance of the proposed methods approximate to that of the conventional scheme with high complexity reduction.

This paper is organized as follows. After this introduction, Section II describes SIC-MMSE based JIDD for massive MIMO systems. Section III presents the proposed complexity reduction schemes with the NSE, and Section IV demonstrates bit error rate (BER) performance simulation results. Finally conclusions are drawn in Section V.

Ⅱ. SIC-MMSE based JIDD

We consider a $M\times N$ large-scale MIMO system, where M is the number of transmit antennas and N is the number of receive antennas. Figure 1 shows a MIMO system with JIDD at the receiver. Information bits in each frame are mapped onto symbols for transmission, denoted by $\mathbf{x}=[x_1,x_2,\cdots,x_M]^T$. We assume energy at each transmit antenna is equally distributed, and channel coefficients are known at the receiver. Then, the received signal, denoted by $\mathbf{y}=[y_1,y_2,\cdots,y_N]^T$, can be represented with a complex channel matrix as follows:

$$\mathrm{y} = \mathrm{H}\mathrm{x} + \mathrm{n}, \tag{1}$$

where n is a complex additive white Gaussian noise vector whose entries follow $CN(0,\sigma^2)$. H is the channel matrix, which can be usually obtained through time-domain and/or frequency-domain training pilots.

The JIDD scheme in Fig. 1 is operated with three loops; the firs loop is inside the iterative channel decoder, the second loop is between the MIMO detector and channel decoder, and the third loop is inside the SIC-MMSE based MIMO detector. In JIDD systems, the accurate estimation of soft information should be conditioned, because the estimation result determines the final decoding performance. Through the exchange of information with the FEC decoder, the detector can explore the correlation of data bits in a codeword and improve its decision based on the knowledge of the codeword inter-dependencies.

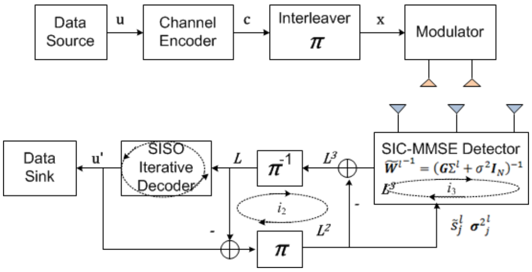

그림 1. SIC-MMSE 검출을 이용하는 MIMO 시스템을 위한 JIDD
Fig. 1. JIDD using SIC-MMSE detection for MIMO system

Ⅲ. The proposed scheme

3.1 SIC-MMSE with three loops

After receiving the transmitted information for a $M \times N$ massive MIMO system with $N \gg M$, we adopt a single matrix inversion based SIC-MMSE scheme. The SIC-MMSE is a MMSE based MIMO detection scheme with soft-in soft-output capability, so the soft vlaues should be estimated during its MMSE filtering process[2]. Assuming three loop JIDD scheme in Fig. 1, the SIC-MMSE process first estimates the expected value of the jth transmitted symbol at the lth iteration at the third loop, $\bar{s}_j^l$ can be estimated using (2).

$$\bar{s}_j^l = \sum_{q \in C} q \prod_{k=1}^{K} \frac{1}{2}\left(1 + \tilde{x}_{j,k} \tanh\left(L^2(x_{j,k}) + L^3(x_{j,k})\right)\right). \tag{2}$$

In (2), K is the number of bits per symbol, L^2 and L^3 are the log-likelihood ratio (LLR) soft values produced from the channel decoder and the previous SIC-MMSE detection process as shown in Fig. 1. $\widetilde{x_{j,k}}$ is considered as ± 1 depending on the complex symbol q comprised in the constellation set, *C*. The variance of $\bar{s}_j^l$ represents the reliability of each calculated soft symbols. We can compute it as follows:

$$\sigma^{2^l_j} = \sum_{q \in C} |q|^2 \prod_{k=1}^{K} \frac{1}{2}\left(1 + \tilde{x}_{j,k} \tanh\left(L^2(x_{j,k}) + L^3(x_{j,k})\right)\right) - |\bar{s}_j^l|^2. \tag{3}$$

In comparison with the method of estimating soft values in reference [2], we employed both of L^2 and L^3 together independent of the layer. In other words, at the first iteration of the third loop, $L^3 = 0$, this make it more efficient estimation of soft values in (2) and (3). Next, the interference-cancelled symbol vector for the ith layer, $\hat{\mathrm{y}}_i^l$ is estimated by

$$\hat{\mathrm{y}}_i^l = \mathrm{H}^H \mathrm{y} - \sum_{j, j \neq i} \mathrm{g}_j \bar{s}_i^l = \mathrm{h}_i s_i + \tilde{\mathrm{n}}_i^l. \tag{4}$$

In (4), h_i is the ith column of the channel matrix, $\tilde{\mathrm{n}}_i^l$ denotes the residual noise plus interference, g_j is the jth column of Gram matrix $\mathrm{G} = \mathrm{H}^H \mathrm{H}$. For a massive MIMO system with $N \gg M$, the matrix G can be approximated to a diagonal matrix.

Then, letting $\widetilde{\mathrm{W}}^l = \left(\mathrm{G}\Sigma^l + \sigma^2 \mathrm{I}_N\right)$, the layer independent MMSE filtering matrix, W^l is calculated as follows[3]:

$$\mathrm{W}^l = \left(\mathrm{G}\Sigma^l + \sigma^2 \mathrm{I}_N\right)^{-1} = \left(\widetilde{\mathrm{W}}^l\right)^{-1}, \tag{5}$$

and the layer-independent variance matrix, Σ^l is formed by

$$\Sigma^l = \mathrm{diag}\left\{\sigma^{2^l_1}, \sigma^{2^l_2}, ..., \sigma^{2^l_N}\right\}. \tag{6}$$

Accordingly, we can assume that $\widetilde{\mathrm{W}}^l$ can be approximated to a diagonal matrix when $N \gg M$ and as l is increased[5]. More detailed process of applying conventional SIC-MMSE filtering process can be found in references [2] and [3]. In the following, we propose a complexity reduction scheme by utilizing this diagonal-like characteristics of $\widetilde{\mathrm{W}}^l$.

3.2 Complexity reduction by the NSE method

The NSE approximates the matrix inversion process to a infinite summation of matrix multiplications when a matrix can be decomposed to a diagonal matrix[6]. As (5) shows, $\widetilde{\mathrm{W}}^l$ is close to a diagonal matrix when the number of receiving antennas increases, because G can be approximated to a diagonal matrix.. By decomposing $\widetilde{\mathrm{W}}^l$ as $\widetilde{\mathrm{W}}^l = \mathrm{D}^l + \mathrm{E}^l$, where D^l is a matrix with diagonal elements of $\widetilde{\mathrm{W}}^l$ and E^l is a matrix with off diagonal parts, then W^l can be rewritten as:

$$\begin{aligned}\mathrm{W}^l &= \left(\mathrm{G}\Sigma^l + \sigma^2 \mathrm{I}_N\right)^{-1} \\ &= \left(\mathrm{D}^l + \mathrm{E}^l\right)^{-1} = \sum_{n=0}^{\infty}\left(-\mathrm{D}^{l^{-1}}\mathrm{E}^l\right)^n \mathrm{D}^{l^{-1}}.\end{aligned} \tag{7}$$

The above (7) can be well approximated if the elements in D^l is more dominant than the ones in E^l, even with a small number of terms in the summation. Therefore, if we approximate W^l by using only the first two terms in the summation, i.e., with n = 0 and 1, then (7) can be simply approximated as follows:

$$\begin{aligned}\mathrm{W}^l &\approx \left(-\mathrm{D}^{l^{-1}}\mathrm{E}^l\right)^0 \mathrm{D}^{l^{-1}} + \left(-\mathrm{D}^{l^{-1}}\mathrm{E}^l\right)^1 \mathrm{D}^{l^{-1}} \\ &= \mathrm{D}^{l^{-1}} - \mathrm{D}^{l^{-1}}\mathrm{E}^l\mathrm{D}^{l^{-1}}.\end{aligned} \tag{8}$$

Even though there is a matrix inversion, $\mathrm{D}^{l^{-1}}$ in (8), the computation of $\mathrm{D}^{l^{-1}}$ is just simple scalar inverse operations of diagonal elements. Comparing with the computational complexity of calculating an inverse matrix with the Gauss–Jordan elimination approach, which is $O(M^3)$, the proposed method using the NSE with first two terms as in (8) only requires $O(M^2)$ operations[6].

The output of the SIC-MMSE filter at the ith layer during the lth iteration of detector, $\dot{s}_j^l$ is computed by

$$\dot{s}_j^l = \frac{\mathrm{w}_i^l \hat{\mathrm{y}}_i^l}{\mathrm{w}_i^l \mathrm{h}_i}, \tag{9}$$

where w_i^l is the ith row of matrix W^l.

Ⅳ. Simulation Results

In this section, we compare the performances of the conventional SIC-MMSE detection scheme and the proposed complexity reduced scheme for coded massive MIMO systems. The BER performances against E_b/N_0 (dB) are compared, where E_b/N_0 denotes bit energy to noise spectral density ratio. Modulated signals with 64-quadrature amplitude modulation (QAM) are transmitted through 4×16, 8×64, and 16×64 MIMO systems over a Rayleigh fading channel. For activation of the first loop which is iterations inside the channel decoder, a turbo code is employed for the 4×16 MIMO system, while a low density parity check (LDPC) code is employed for 8×64, and 16×64 MIMO systems.

The turbo code employed for the 4×16 MIMO system has an interleaver size of 378 bits and a code rate of 1/3. The constraint length of the component recursive systematic convolutional (RSC) code inside the turbo code is 3. The number of iterations in the decoding loop for the turbo code is limited to

6 with which the decoding performance is almost saturated. On the other hand, the LDPC code for the 8×64, and 16×64 MIMO systems has a codeword size of 16200 bits and a code rate of 1/2. For iterative decoding for the LDPC code, a min-sum algorithm is used and the maximum number of iterations in the decoding loop is limited to 20.

Figures 2 to 4 show the BER performances of the proposed complexity reduction method with a layer independent matrix inversion simplified by the NSE method, in comparison with the conventional SIC-MMSE detection with a layer independent matrix-inversion process[3]. In the figures, i_2 is the number of iterations at the second loop which is the iteration between the channel decoder and the SIC-MMSE detector, while i_3 is the number of iterations inside the SIC-MMSE detector.

Figure 2 shows the BER performance comparison for the 4×16 MIMO system with the turbo code. Even though the proposed method shows appreciable performance degradation at the initial iteration, i.e. when $i_2 = i_3 = 1$, compared with the conventional scheme, the performance of the proposed scheme approximates to that of the conventional scheme even with 2 iterations for each, i.e. when $i_2 = i_3 = 2$ with an order of less complexity.

Figure 3 and 4 are the BER performances for the 8×64 and 16×64 MIMO systems with the LDPC code. As in the previous investigation, even though

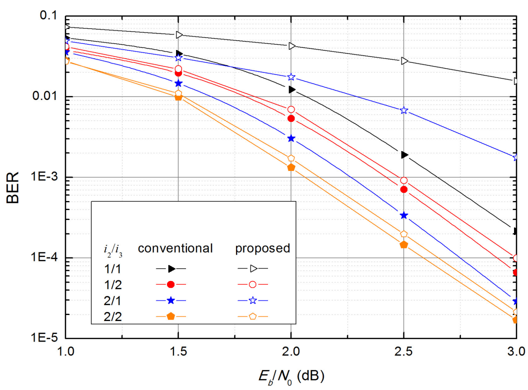

그림 2. 터보 부호화된 4×16 MIMO 시스템에 대한 BER 성능 비교
Fig. 2. BER performance comparison for the turbo coded 4×16 MIMO system

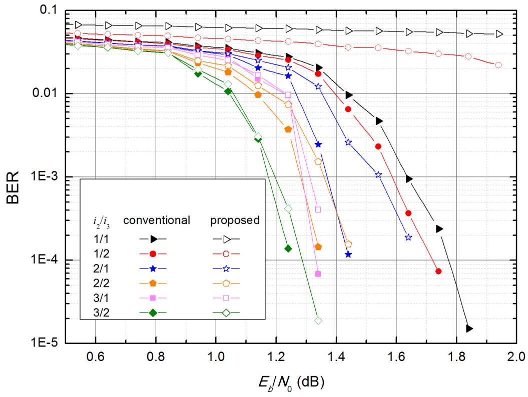

그림 3. LDPC 부호화된 8×64 MIMO 시스템에 대한 BER 성능 비교
Fig. 3. BER performance comparison for the LDPC coded 8×64 MIMO system

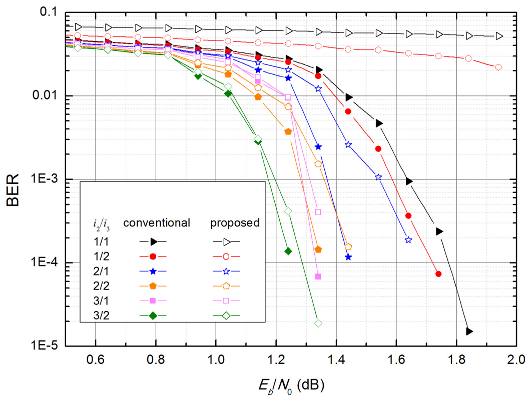

그림 4. LDPC 부호화된 16×64 MIMO 시스템에 대한 BER 성능 비교
Fig. 4. BER performance comparison for the LDPC coded 16×64 MIMO system

we have serious performance degradation at the initial iteration, the proposed scheme shows approximated performance to the conventional scheme if we reach $i_2 = i_3 = 2$. Because the LDPC code has more powerful error correction capability than the turbo code used for the 4×16 MIMO system, we can see the BER performance improvements when $i_2 > 2$ for both 8×64 and 16×64 systems.

Even though the ratio of the number of receive antennas and the number of transmit antennas, i.e., N/M is the same for the 4×16 and 16×64 systems, we can see more evident performance degradation of the proposed scheme for the 16×64 system. This is because the absolute number of antennas is increased for the 16×64 system. Nevertheless, the proposed scheme shows a close performance to the conventional scheme.

V. Conclusion

In this paper, we introduced the NSE based SIC-MMSE detection schemes with JIDD for massive MIMO systems in order to reduce the computational complexity. The BER simulation results of the proposed scheme were demonstrated by using 4×16, 8×64, and 16×64 MIMO systems, with joint iterative detection and decoding scheme. Two different kinds of channel coding schemes with soft iterative decoding capability were used in the simulation, and all the BER performance results showed the approximated performances to the conventional scheme with a reduced complexity of $O(M^2)$ from $O(M^3)$. From the simulation results demonstrated in this paper, we could find the potentials of the proposed method to a higher order massive MIMO system. Future research may include performance investigation of massive MIMO systems with a larger number of antennas.

References

[1] C. Studer, S. Fateh, and D. Seethaler, “ASIC implementation of soft-input soft-output MIO detection using MMSE parallel interference cancellation,” *IEEE J. Solid-State Cir.*, vol. 46, no. 7, pp. 1754-1765, Jul. 2011.

[2] S. Ahmed and S. Kim, “Efficient SIC-MMSE MIMO detection with three iterative loops,” *Int. J. Electron. and Commun.*, vol. 72, pp. 65-71, Feb. 2017.

[3] S. Ahmed, F. Iqbal, M. Zhang, and S. Kim, “Complexity reduced MIMO detection with three iterative loops,” in *Proc. 2017 ICTC*, pp. 213-216, Jeju Island, Korea, Oct. 2017.

[4] Z. Fu and S. Kim, “Low- complexity iterative SIC-MMSE detection for massive MIMO systems,” in *Proc. KICS Summer Conf.*, Jeju Island, Korea, Jun. 2018.

[5] L. Dai, X. Gao, X. Su, S. Han, C-L. I, and Z. Wang, “Low- complexity soft-output signal detection based on Gauss-Seidel method for uplink large-scale MIMO systems,” *IEEE Trans. Veh. Technol.*, vol. 64, no. 10, pp. 4839-4845, Nov. 2015.

[6] M. Wu, B. Yin, A. Vosoughi, C. Studer, J. R. Cavallaro, and C. Dick, “Approximate matrix inversion for high-throughput data detection in the large-scale MIMO uplink,” in *Proc. 2013 IEEE Int. Sym. Cir. and Syst.*, pp. 2155-2158, Bejing, China, May 2013

[7] X. Gao, L. Dai, Y. Hu, Z. Wang, and Z. Wang, “Matrix inversion-less signal detection using SOR method for uplink large-scale MIMO systems,” in *Proc. IEEE GLOBECOM*, pp. 3291-3295, Austin Texas, USA, Dec. 2014.

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