Iterative Interference Cancellation and Decoding for Convolutional Coded VBLAST Systems

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Abstract—In this paper, we present an iterative interference cancellation (IIC) and decoding scheme that significantly improves the performance of coded VBLAST systems. We show that due to the residue interference caused by incorrect decisions from the previous iteration, the distribution of the total noise in the IIC process is non-Gaussian. Euclidean distance, therefore can not be used as the bit metric in soft decision Viterbi decoding. To preserve the Gaussian distribution of the total noise, we propose to use soft nulling for VBLAST detection. We also propose a scheme employing soft decision Viterbi decoding with IIC (SDD-IIC) and demonstrate that it significantly improves both the coding gain and diversity gain of the VBLAST system.

I. INTRODUCTION

It was shown in [1] that large capacity can be exploited in rich scattering wireless channels by employing multiple antennas at both the transmitter and the receiver. Among various Multiple Input Multiple Output (MIMO) system structures, Vertical Bell Labs Space Time (VBLAST) system [3] [4] has the advantage of easy implementation and therefore attracted a lot of attention for practical deployment. The reported spectral efficiency of the prototype VBLAST system reaches 20-40 bps/Hz at average SNR of 24-34 dB [4].

Error control coding (ECC) can be employed in VBLAST systems to improve its robustness against fading. In [5], it was shown that independent ECC on each data stream (horizontal coding) results in the best performance, compared with vertical coding and hybrid coding structures. Therefore, in this paper, we focus on the study of horizontal encoding with convolutional code. Figure 1 depicts the diagram of a horizontal-coded VBLAST system transmitter, on which the encoding, interleaving and constellation mapping are performed independently on each data stream.

Fig. 1. Horizontal-coded VBLAST system transmitter

The interference nulling and cancellation (INC) scheme employed in VBLAST system does not fully exploit the diversity in the system. To improve the diversity gain, we propose to use an iterative interference cancellation (IIC) detection scheme. In the first iteration, INC can still be applied. Such an INC scheme on one hand improves the performance, the decision errors in the previous iteration, on the other hand, makes the distribution of the overall noise non-Gaussian. Therefore, Euclidean distance can no longer be used as the bit metric in soft decision decoding. As binary symmetric channel property is still satisfied, hard decision decoding is still optimal and can be used at the end of the IIC process.

Hard decision decoding, however, can only provide limited coding gain. In order to apply soft decision decoding in non-Gaussian noise channel, we may estimate the probability density function (PDF) of the total noise, and compute the bit metric accordingly. Estimation of PDF in a real time system, however, is rather difficult and with limited accuracy. Calculation of the bit metric also adds extra complexity to the decoder.

In this paper, we propose a soft decision decoding with IIC (SDD-IIC) scheme. In this scheme, we use a soft nulling technique in the first iteration of the detection, which maintains the Gaussian property of the total noise and enables the Euclidean distance-based bit metric in soft decision Viterbi decoding. The output of the soft decision decoder is then used to estimate the interference through re-encoding, interleaving and mapping. In this way, the residual interference becomes rather small and hence insignificant when compared with the Gaussian noise term, as shown later by our data sample statistics analysis. The Euclidean distance is therefore an accurate approximation of the bit metric. Although exchange of soft information between the decoder and the detector, as in [6], leads to better performance, the implementation is rather complex. The complexity of the proposed SDD-IIC, as we are going to show later, is much lower. Our computer simulations demonstrate that this scheme significantly improves the coding gain as well as the diversity gain of the VBLAST system. As the performance of the proposed scheme is close to the BER performance bound, we claim the SDD-IIC provides a good compromise between good performance and low system complexity.

We use the following notations in this paper: vectors as bold lower case letters, and matrices as bold upper case letters. All vectors are in column form. We use the superscripts $H$ and $*$ to denote matrix Hermitian and conjugation, respectively. The elements of vectors/matrices are denoted by letters with subscripted indices.
II. INTERFERENCE CANCELLATION AND DISTRIBUTION OF THE TOTAL NOISE

For a \( m \times n \) (\( m \) denotes the number of transmit antennas and \( n \) denotes the number of receive antennas) VBLAST system, the received signal is given by

\[
 r = Hx + n, \tag{1}
\]

where \( H \) is a \( n \times m \) channel matrix with \( H_{i,j} \) representing the channel response between transmit antenna \( j \) and receive antenna \( i \). \( x \) denotes the transmit signal from \( m \) transmit antennas and \( n \) is the AWGN noise vector.

From (1), we can see that the received signal is a mixture of signals from all the transmit antennas. The VBLAST detection can be performed as

\[
 y^i_k = [h^i_x]^T x^i + h^i_n, \tag{4}
\]

where \( h^i_x \) is the \( i \)th column of \( H \) and \( x^i \) is the transmitted signal from the \( i \)th transmit antenna. Firstly, we perform conventional interference and hence, perform interference cancellation. For systems working at practical SNR values, however, this can hardly be achieved. Hence, the total noise comprises both the AWGN noise and the residue interference.

To analyze the distribution of the total noise, data samples were collected through computer simulations. The channel coefficients are uncorrelated zero-mean complex Gaussian random variables and we also assume perfect channel estimation at the receiver. Figure 2 shows the histogram of the total noise in comparison with a standard Gaussian distribution after different iterations given in the IEEE 806.11a standard [7] with a code rate of 1/2 and constraint length of 7. The generator polynomials are \( g_0 = 133_b \) and \( g_1 = 171_b \), respectively. Interleaving is done in two stages. The first stage maps adjacent coded bits onto less and more significant subcarriers while the second guarantees that adjacent coded bits are mapped alternately onto less and more significant bits of the constellation [7].

From Figure 3, we can see the non-Gaussian noise distribution severely degrades the performance of the soft decision Viterbi decoding. At high SNR values, it is even worse than hard decision decoding. Hence, in this case, there are no advantages of using soft, Euclidean distance based, bit metric in the decoding process than using hard decision. It should be noted that

\[
y^i_k = [h^i_x]^T x^i + h^i_n, \tag{5}
\]
the performance of hard decision decoding is not affected by the non-Gaussian total noise, because the binary symmetric channel property is still satisfied and hard decision Viterbi decoding is still optimal.

As a result, for each transmitted data stream, we have the corresponding detection output that consists only the attenuated signal component and an AWGN noise. The difference between this approach from the conventional interference nulling approach is that here we use a nulling vector with unit norm. It cancels the interference from the other transmit antennas, and at the same time, it does not equalize the attenuation introduced by the channel as what the conventional nulling does. This does not change the power distribution of the channel noise on different receive antennas as the nulling vector has unit norm. We refer it as soft nulling in the subsequent discussions.

Zero forcing nulling suffers from the problem of noise enhancement. Therefore, it is more advantageous to use MMSE nulling in practice. In such case, the nulling vector is given by

$$w^n_i = h^n_i (HH^n + \sigma^2 I)^{-1}. \quad (8)$$

However, the diversity order of the signal after soft nulling is only $n - m + 1$. To fully exploit the potential diversity of the system, we propose to combine the soft decision decoding with the IIC technique.

Fig. 3. Comparison of BER for soft decision decoding and hard decision decoding for non-Gaussian total noise.

**III. SOFT DECISION DECODING WITH ITERATIVE INTERFERENCE CANCELLATION**

In Section II, we showed that the distribution of the total noise is non-Gaussian and Euclidean distance can no longer be used as the bit metric in soft decision Viterbi decoding. Hence, for VBLAST system employing INC detection, it is more advantageous to use hard decision decoding, which has a much lower complexity and close performance compared to Euclidean distance based soft decision decoding. However, the BER performance of hard decision decoding is rather limited. To improve the performance of soft decision decoding in such non-Gaussian noise channel, we may estimate the probability density function (PDF) of the total noise using data samples and calculate the bit metric accordingly. However, the PDF estimation in real-time systems is rather difficult and the limited accuracy usually leads to only small improvement in the performance [8]. Moreover, the calculation of bit metric using the estimated PDF imposes extra complexity to the decoder. In this section, we propose an iterative decoding and detection algorithm that can effectively mitigate the non-Gaussian interference and improve the BER performance significantly through a few iterations.

In this approach, we propose to use nulling technique to remove the residue interference from (4). Let $w_i$ be an unit vector and orthogonal to the interference subspace, i.e.

$$w_i^H H_{\text{inf}} = [0, 0, \cdots, 0], \quad (6)$$

and multiplying $w_i^H$ with the received signal vector $r$, we have

$$y_i = w_i^H r$$
$$= w_i^H h_i x_i + w_i^H n$$
$$= g_i^T x_i + w_i^H n. \quad (7)$$

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Fig. 4. SDD-IIC for coded VBLAST system.

Figure 4 shows the system diagram of the soft decision decoding with IIC (SDD-IIC). In this scheme, we first decode the soft nulling output using soft decision decoding and then, re-encode the decoded bits to form the estimate of the transmitted signal vector $\hat{x}$. This is actually a process to feed back the hard decision information from the decoder to the detector. Through the process of decoding and re-encoding, we are able to correct some errors in the previous iteration and produce a better estimate of the transmitted signal vector $x$.

Figure 5 shows symbol error rate (SER), which directly reflects the amount of the residue interference, of the estimated signal from re-encoding the output of the soft nulling and soft decision decoder. In comparison, we also present the SER of the hard decision output from the conventional INC detector. The SER of the estimated signal after decoding and re-encoding, as

$$w_i^n = h^n_i (HH^n + \sigma^2 I)^{-1}. \quad (8)$$

In general $w_i^H w_j^H \neq 0$ for $i \neq j$. The noise at different data streams are, therefore, correlated. However, as decoding is performed independently on each data stream, the noise seen by the decoder is still AWGN.

$w_i^n$ needs to be normalized to unit norm.
expected, is much lower compared to the SER of the INC detector output. Therefore, the residue interference in the next iteration of interference cancellation is significantly reduced compared to IIC case.

Fig. 5. Comparison of symbol error probability of the hard decision output after INC and the reconstructed signal after SDD.

We studied the histogram of the total noise after different iterations for the SDD-IIC scheme. Figure 4 shows the noise distribution at Eb/N0 of 9dB and 13dB respectively, for a 4 x 4 VBLAST system. With the feedback of hard decision information from the decoder to the detector, the probability of decision errors is effectively reduced. As a result, the AWGN noise becomes more dominant and the distribution of the total noise is close to Gaussian. As SNR increases from 9dB to 13dB, the Gaussian noise becomes more dominant and hence the noise is almost identical to Gaussian distribution. Moreover, as the number of iterations increases, the interference becomes negligible due to the good performance of soft decision decoding. For both SNR’s, we can see, from Figure 6, that the distribution of the total noise is effectively Gaussian after the 1st iteration.

Fig. 6. Distribution of the total noise for a coded 4 x 4 VBLAST system with SDD-IIC.

To calculate the bit metric of the soft decision decoder, we denote \( b_i^k \) as the \( k \)th bit of \( x_i \) and \( X^k_i \) as a subset of all the constellation points \( X \), whose elements have the value of \( b \in \{0, 1\} \). at position \( k \). The bit metric for the \( k \)th bit of \( x_i \) in (4) for a particular iteration \(^3\) can be written as [9]

\[
\lambda_{i,k}(y_i, b) = \log \left[ \frac{P(y_i|b_i^k = b, ||h_i||^2)}{2^{(M-1)} \log \sum_{x_i \in X^k_i} P(y_i|x_i, ||h_i||^2)} \right], \quad (9)
\]

where \( P(x) \) denotes the PDF of \( x \), and \( M \) is the constellation order. The bit metric in (9) can be approximated by a simple computational form [9]

\[
\lambda_{i,k}(y_i, b) = \max_{x_i \in X^k_i} \log \left[ P(y_i|x_i, ||h_i||^2) \right]. \quad (10)
\]

As the Gaussian noise dominate the total noise using the proposed SDD-IIC scheme, we can ignore the residue interference term in 4 in the calculation of the bit metric for soft decision decoding. Hence, (10) can be further written as:

\[
\lambda_{i,k}(y_i, b) = \log \left[ \frac{1}{\sqrt{2\pi\sigma^2}} \exp \left(-\frac{(y_i - ||h_i||x_{i,\text{max}})^2}{2\sigma^2} \right) \right] \quad \lambda_{i,k}(y_i, b) = \frac{1}{\sqrt{2\pi\sigma^2}} \left[ -\frac{(y_i - ||h_i||x_{i,\text{max}})^2}{2\sigma^2} \right] \quad (11)
\]

where \( \sigma^2 \) is the variance of the AWGN noise and \( x_{i,\text{max}} \) is the signal that maximizes (10). The final expression for the bit metric is given by

\[
\lambda_{i,k}(y_i, b) = \frac{y_i}{||h_i||} - \frac{y_i}{x_{i,\text{max}}}. \quad (12)
\]

With the bit metric given by (12), we carried out simulations to study the performance of the SDD-IIC scheme. Here, we used MMSE soft nulling technique to remove the interference from other transmit antennas. The channel model, encoder and interleaver used in the simulations are the same as those used in Section II. Figure 7 and Figure 8 show the BER performance of the SDD-IIC for a 4 x 4 and an 8 x 8 VBLAST system respectively. Also shown in the figure is the lower bound of BER performance of proposed scheme. The bound is obtained by assuming that all the estimated transmitted signals feed back for interference cancellation are correct, such that the interference from the other transmit antennas can be removed completely. Hence, we have effectively an \( n \)-antenna receive diversity system with soft decision Viterbi decoding.

We can see that the BER performance of the VBLAST system improves significantly through iterations for both systems. For the 4 x 4 VBLAST system, performance gain of more than 6 dB can be achieved by using 3 iterations compared no iteration is performed at BER of \( 10^{-3} \). For the 8 x 8 system, the performance gain is about 7 dB at BER of \( 10^{-3} \). Moreover, if we compare the slope of the BER against SNR curve, we can see that the proposed scheme enhances the diversity gain of the VBLAST system as well. Therefore, we expect higher gain in BER when

\(^3\)We omit the iteration index here for clearer notation.
SNR increases. After 3 iterations, the difference between the performance of SDD-IIC scheme with the performance bound for a $4 \times 4$ system is 2.1 dB. For $8 \times 8$ system, this difference is reduced to 1.6 dB.

The proposed SDD-IIC scheme is a process where soft information is passed from the detector to the decoder, while hard information from decoder to detector. Although exchange of soft information in both directions, as done in [6], leads to BER performance that is closer to the lower bounds given in Figure 7 and Figure 8, the complexity of such scheme is rather high. Moreover, in real implementation, it is not necessary to perform the re-encoding process. This is because in the Viterbi decoding, the code words and the decoded bits of the survival path can be recorded. The extra complexity of the proposed scheme, hence, only involves an interleaver and a constellation mapper. Moreover, as the performance of SDD-IIC scheme is already very close to the lower bound, which is also the lower bound for Turbo BLAST system, the improvement by using Turbo BLAST structure is not going to be significant. Therefore, SDD-IIC algorithm provides a good trade-off between good system performance and low complexity.

IV. CONCLUSION

In this paper, we proposed an iterative interference cancellation and decoding scheme and studied its performance on convolutional-coded VBLAST systems. We showed that the total noise in the IIC process has a non-Gaussian distribution due to the residue interference from the erroneous decisions in the previous iteration. To maintain the Gaussian distribution of the total noise, we proposed to use soft nulling technique. We introduced the SDD-IIC algorithm, which combines soft decision decoding and iterative interference cancellation. We showed that the residue interference is reduced significantly by re-encoding the output of the soft decision decoder in the SDD-IIC process. As a result, the total noise is dominated by AWGN noise and standard Euclidean distance based soft decision decoding can be employed without modification. Simulations show the SDD-IIC scheme significantly improves the performance of the coded VBLAST system in terms of both coding gain and diversity gain.

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REFERENCES