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Correspondence

Turbo Diversity Based on SC/MMSE Equalization

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Abstract—In this paper, an iterative (turbo) technique, soft-cancellation followed by minimum mean squared error filtering (SC/MMSE), is applied to the diversity combining of broadband single-carrier signals using multiple antennas. The major aim of this approach is to reduce the computational complexity of the original SC/MMSE equalization algorithm. It is shown that the performance of the proposed turbo diversity technique can asymptotically achieve that of the original SC/MMSE equalizer.

Index Terms—Diversity combining, minimum mean squared error (MMSE) filtering, soft interference cancellation, turbo equalization.

I. INTRODUCTION

Recently, turbo equalization techniques have attracted a lot of attention because of their relatively low computational complexity and excellent performance [1], [2]. However, if the equalizer requires the channel's trellis diagram, its computational complexity increases exponentially with the equalizer length, which may still be prohibitive in broadband single carrier transmission.

The complexity-reduced iterative turbo technique, soft cancellation followed by minimum mean squared error filtering (SC/MMSE) [3], [4], requires a cubic order complexity $O(L^3 M^3)$, with L and M being the number of propagation paths and receive antennas due to the matrix inversion needed for the MMSE filter coefficient calculation. To avoid the matrix inversion, approximation techniques have been proposed in [5] and [6], by which the complexity can further be reduced.

This paper proposes another technique to reduce the complexity without approximating the SC/MMSE algorithm itself. The receiver antenna elements are split into groups in which the SC/MMSE signal processing is first performed independently. After a sufficient number of SC/MMSE iterations, the obtained log likelihood ratios (LLRs) are propagated crosswise between the soft-input soft-output (SISO) channel decoders in each group. Finally, their bit-wise LLRs are combined for the final decision. This configuration is referred to as turbo diversity.

The major objective is to show that the proposed turbo diversity technique can reduce the complexity of SC/MMSE and the performance of the original SC/MMSE equalizer can be asymptotically approached by the proposed turbo diversity.

This paper is organized as follows. Section II describes the communication channel model used in this correspondence. A mathematical space-time representation of the channel is given. Section III briefly summarizes the algorithm presented in [3]. Section IV derives the proposed turbo diversity receiver configuration and presents the results of computer simulations conducted to evaluate its performance. Conclusions are given in Section V.

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II. CHANNEL MODEL

Single-input multiple-output (SIMO) case is considered. Information bits to be transmitted are first encoded by the channel encoder. After the interleaving and the modulation, the symbols $b(k)$ are transmitted via a single transmit antenna over frequency selective channels. The receiver is employed with M antennas. A discrete time representation of the received signal at the m th antenna is

$$r_m(k) = \sum_{l=0}^{L-1} h_m(l)b(k-l) + v_m(k) \quad (1)$$

where $h_m(l)$ is a discrete time representation of the channel between the transmitter and the m th receiver antenna and $v_m(k)$ is additive white Gaussian noise. Signal samples received by M antennas are expressed as

$$\underline{r}(k) = [r_1(k) r_2(k) \dots r_M(k)]^T. \quad (2)$$

When temporal sampling is performed to capture the multipath signal, it yields the following space-time representation of the received signal vector $y(k)$:

$$\begin{aligned} \underline{y}(k) &= [\underline{r}^T(k+L-1) \dots \underline{r}^T(k)]^T \\ &= \underline{H} \cdot \underline{b}(k) + \underline{V}(k) \end{aligned} \quad (3)$$

where

$$\underline{H} = \begin{bmatrix} H(0) & \dots & H(L-1) & \dots & 0 \\ & \ddots & & \ddots & \\ 0 & & H(0) & \dots & H(L-1) \end{bmatrix} \quad (4)$$

is the channel matrix with

$$H(l) = [h_1(l) h_2(l) \dots h_M(l)]^T, \quad l = 0, 1, \dots, L-1 \quad (5)$$

and $\underline{b}(k)$ and $\underline{V}(k)$ being

$$\underline{b}(k) = [b^T(k+L-1) \dots b^T(k) \dots b^T(k-L+1)]^T \quad (6)$$

and

$$\underline{V}(k) = [\underline{v}^T(k+L-1) \dots \underline{v}^T(k)]^T \quad (7)$$

with

$$\underline{v}(k) = [v_1(k) v_2(k) \dots v_M(k)]^T. \quad (8)$$

III. SC/MMSE TURBO EQUALIZER

Since the details of the mathematical derivation of the SC/MMSE algorithm are presented in [3], this section only summarizes the algorithm. The equalizer consists of an SC/MMSE part and a SISO decoder. The SC/MMSE part delivers the LLR of each symbol in a frame. After

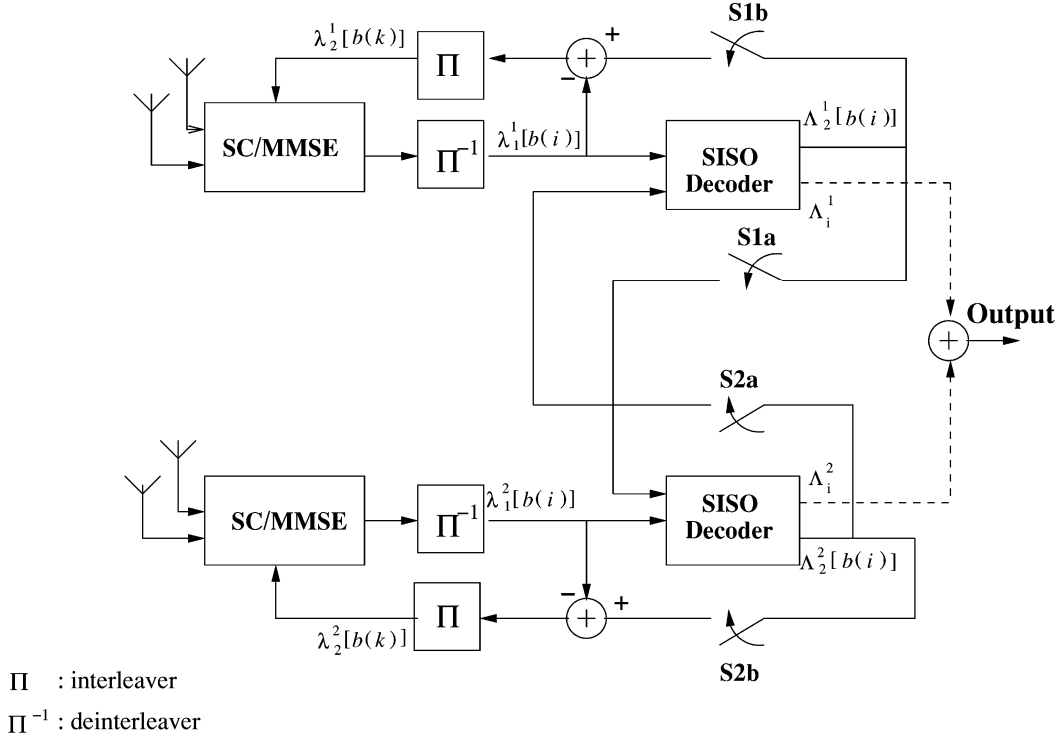


Fig. 1. The structure of the single user SC/MMSE turbo diversity scheme.

deinterleaving the LLR values, SISO decoding is performed. The updated LLRs are fed back to the SC/MMSE part, which performs the SC/MMSE signal processing again. This process is repeated until the convergence of the performance is reached. It should be noted that symbol-wise LLRs obtained from the SC/MMSE part may have to be converted to bit-wise, depending on the decoder used. After decoding, they have to be converted again to symbol-wise before feeding them back to the SC/MMSE part.

SC/MMSE requires the output vector of the multiple antennas, the estimate of the channel matrix \underline{H} , and the soft symbol \hat{b} calculated from the LLR. Multiplying the channel matrix estimate \underline{H} by the soft symbol vector $\underline{u}(k)$

$$\underline{u}(k) = [\hat{b}(k+L-1) \dots \hat{b}(k+1) 0 \hat{b}(k-1) \dots \hat{b}(k-L+1)] \quad (9)$$

the soft estimates of the interfering components can be calculated, which are then subtracted from the antenna output vector as

$$\hat{y}(k) = \underline{y}(k) - \underline{H} \cdot \underline{u}(k). \quad (10)$$

This process is referred to as soft cancellation.

The soft canceller output $\hat{y}(k)$ still has residual interfering components, which can further be suppressed by MMSE filtering. The MMSE filter also combines the multipath components. This iteration process is repeated, resulting in overall performance almost the same as the optimal receiver performance [1].

IV. TURBO DIVERSITY BASED ON SC/MMSE

The computation of the MMSE filter coefficients requires inversion of the covariance matrix of the soft canceller output, with which the complexity is a cubic order $O(L^3 M^3)$ of LM . This leads to the idea that the multiple antenna elements are split into groups, in which the SC/MMSE signal processing first takes place independently. After a

TABLE I
SIMULATION PARAMETERS

Modulation	BPSK
Information bits/frame	256
Number of transmitted frames	10 / (BER exponent)
Channel coding	Convolutional coding (code rate=1/2, constraint length=3)
Channel mode	Equal average power L -path Rayleigh fading, $L = 3, 6$
Interleaver	Random
Channel estimation	Perfect
Number of diversity branches K	2
Number of horizontal iterations HI	4
Number of vertical iterations VI	1

sufficient number of SC/MMSE iterations, the SISO decoders of each group are connected crosswise to enable the exchange of the obtained LLRs between the decoders. Finally, the LLRs of the bits are combined, on which the final decision is made. This configuration is referred to as turbo diversity as noted before, and the groups are referred to as branches in the following.

A. Turbo Diversity

Fig. 1 shows a block diagram of an example of the SC/MMSE turbo diversity receiver, in which four antenna elements are split into two branches. The SC/MMSE equalizers and SISO decoders are connected via two sets of switches {S1a, S2a} and {S1b, S2b}. For initial convergence, the SC/MMSE iteration takes place independently on two branches, i.e., {S1a, S2a} are open and {S1b, S2b} are closed. This process is referred to as a horizontal iteration.

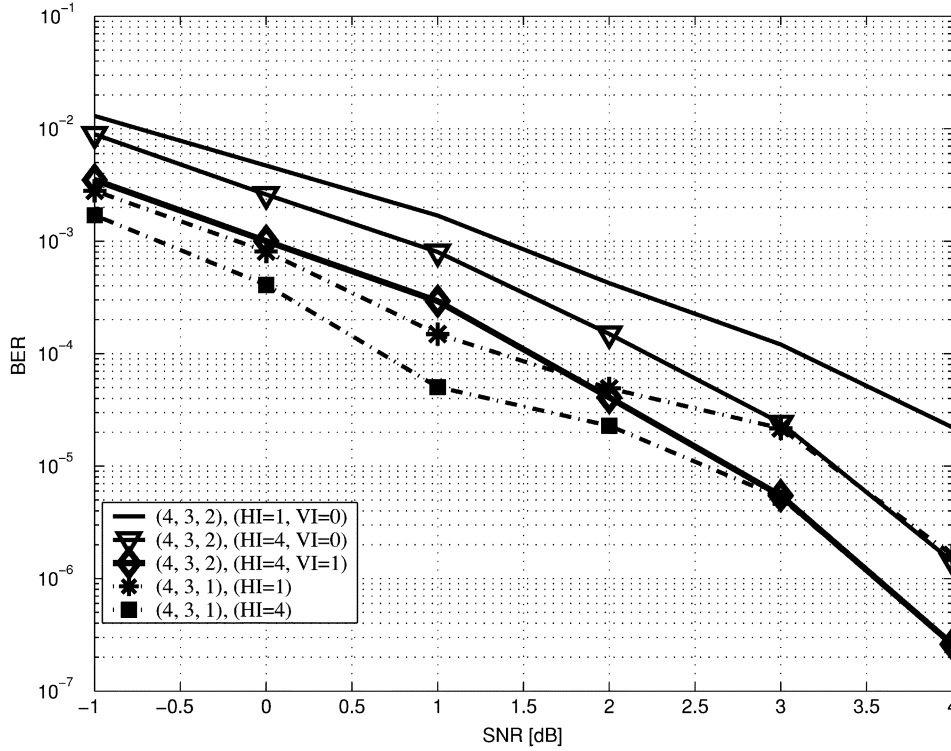


Fig. 2. BER performances with (4, 3, 2) and (4, 3, 1).

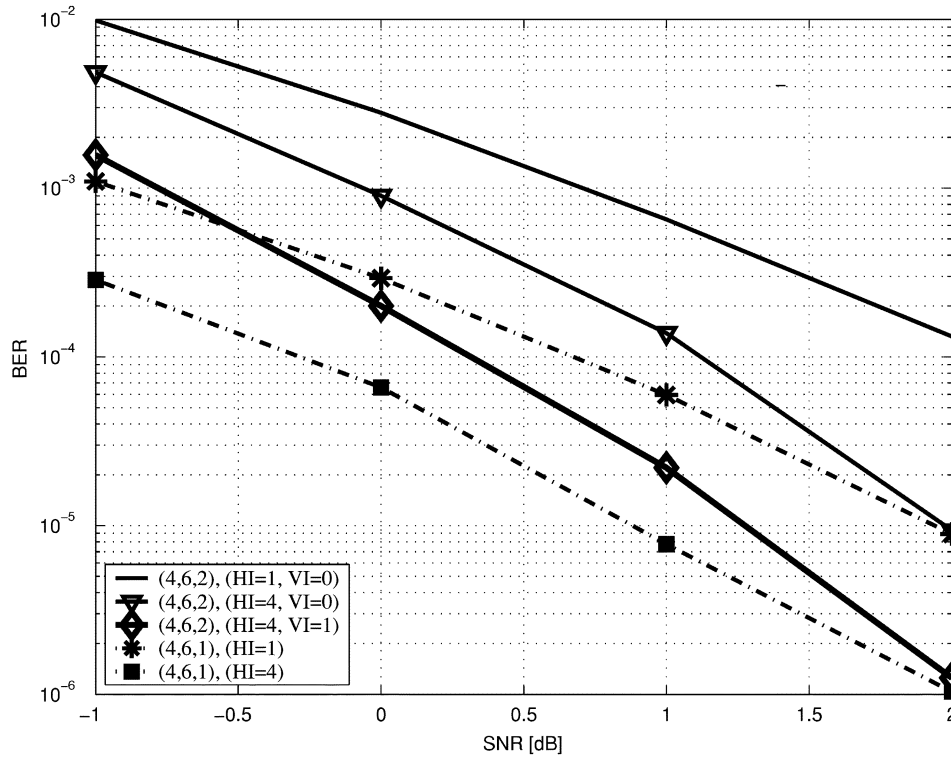


Fig. 3. BER performances with (4, 6, 2) and (4, 6, 1).

The SC/MMSE equalizer on the first branch delivers LLR λ_1^1 for each symbol. After deinterleaving, the LLR is fed to the SISO decoder, which provides updated LLRs of each symbol Λ_2^1 . The value $\lambda_2^1 = \Lambda_2^1 - \lambda_1^1$ is interleaved and then fed back to the SC/MMSE equalizer.

The same process is performed on the second branch to produce $\lambda_2^2 = \Lambda_2^2 - \lambda_1^2$. The λ_2^1 and λ_2^2 values are used to calculate the

soft symbol $\hat{b}(k)$ of $\underline{b}(k)$. This process is repeated. After a sufficient number of horizontal iterations, obtained λ_1^1 and λ_1^2 are stored, switches {S1a, S2a} closed, and {S1b, S2b} opened for vertical iterations.

During the vertical iterations, the LLR values are propagated between the SISO decoders. On the first branch, $\Lambda_2^2 + \lambda_1^1$ is fed to the

SISO decoder, which then provides the updated Λ_2^1 , whereas on the second branch, Λ_2^2 is updated by performing SISO decoding to the sum $\Lambda_2^1 + \lambda_1^2$. After the vertical iterations, the LLRs Λ_i^1 and Λ_i^2 of the bit estimates are combined, on which the final decision is made.

B. Complexity Considerations

The original SC/MMSE requires a cubic order of complexity $O(L^3 M^3)$. If the M antenna elements are divided into K turbo diversity branches, the computational complexity becomes of the order $O(L^3 M^3 / K^2)$. Therefore complexity reduction becomes larger as K becomes larger. The complexity reduction may cause performance degradation, depending on the channel load as well as on the multipath propagation conditions. Thus, the performance–complexity tradeoff has to be considered.

The next section shows that the performance of the turbo diversity receiver can asymptotically approach that of the original SC/MMSE turbo equalizer.

C. Performance Results

In this section, the results of the simulations conducted to evaluate the performance of the proposed turbo diversity receiver are shown. Simulation parameters are summarized in Table I.

Performance with the $(M, L, K) = (4, 3, 2)$ turbo diversity scheme and $(4, 3, 1)$ original SC/MMSE equalizer are compared first. Bit error rate (BER) performance versus received average signal-to-noise ratio (SNR) are shown in Fig. 2. It is found that with one iteration, the BER with $(4, 3, 2)$ is worse than that with $(4, 3, 1)$, but after the vertical iteration, $(4, 3, 2)$ BER performance approaches that of $(4, 3, 1)$ as SNR increases.

Fig. 3 compares the BER performances between the schemes $(M, L, K) = (4, 6, 2)$ and $(4, 6, 1)$. Due to the additional diversity order obtained from the increased number of propagation paths, the BER curves decline more drastically. Also in this case, the performance curve of $(4, 6, 1)$ can be approached by that of $(4, 6, 2)$.

V. CONCLUSION

In this paper, we have presented, for broadband single carrier signaling, an SC/MMSE-based turbo diversity technique that offers lower computational complexity. Performance comparison between the original SC/MMSE and turbo diversity receivers was conducted in frequency-selective fading channels. It has been shown that the BER performance of the proposed turbo diversity receiver asymptotically approaches that of the original SC/MMSE equalizer as the SNR increases.

It should be noted that the turbo diversity technique can easily be extended to multiple-input multiple-output scenarios [7]. It should be further noted that if the frequency-domain SC/MMSE algorithm [8] is used in each turbo diversity branch, the overall computational complexity of the proposed turbo diversity can significantly be reduced.

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