ISIC-MMSE detector for BICM SM-MIMO systems with estimated CSI

Fei F. Cao1,a), Zan Li1, Jiandong Li1, Guanghui Yu2, and Xiaohui Li1

1 State Key Lab. ISN, Xidian University, TaiBai Road No.2, Xi’an, China
2 ZTE Corporation, KejiNanlu No. 55, ShenZhen, China

a)f.f.cao@263.net

Abstract: We study the iterative soft interference cancellation-minimum mean square error filtering (ISIC-MMSE) detector with estimated channel state information (CSI) for bit-interleaved coded modulation (BICM) spatial multiplexing multiple input multiple output (SM-MIMO) systems. By considering the channel estimation errors in all detection modules, we propose a modified ISIC-MMSE detector which considerably outperforms the conventional ISIC-MMSE detector in terms of performance and transmission rate with only moderate complexity increase.

Keywords: SM-MIMO, ISIC-MMSE, estimated CSI

Classification: Science and engineering for electronics

References

1 Introduction

Compared with joint detection algorithms such as the maximum a posteriori probability (MAP) detector and the quasi-MAP detectors (e.g., the list sphere decoder), the ISIC-MMSE detector [1, 2, 3] provides a good trade-off between performance and complexity, which makes it quite suitable for MIMO systems with large symbol constellations and a large number of antennas [2]. In this paper, instead of adopting perfect CSI as in [1, 2, 3], we study the ISIC-MMSE detector with estimated CSI for BICM SM-MIMO systems. For space-time block/trellis coding, a joint decoding with estimated CSI has been proposed in [4], which considers channel estimation errors (CEE) directly in metric calculation of a symbol-vector or a symbol-matrix. However, due to the fact that the ISIC-MMSE detector performs in a symbol-by-symbol manner, the joint decoding in [4] can not be adopted when designing the ISIC-MMSE detector with estimated CSI. Therefore, by redesigning all the three modules of the ISIC-MMSE detector, i.e., soft interference cancellation, MMSE filtering, and metric calculation, we propose a modified ISIC-MMSE detector with estimated CSI (denoted as Mod detector hereafter for conciseness) for BICM SM-MIMO systems. Simulation results demonstrate that as compared with the conventional ISIC-MMSE detector [1, 2, 3] which does not consider the CEE (for conciseness, the ISIC-MMSE detector proposed in [1, 2, 3] is denoted as Conv detector hereafter), the Mod detector can obtain considerable performance gains and transmission rate gains with only moderate complexity increase.

2 System model and conventional ISIC-MMSE detector

We consider a BICM SM-MIMO system with $N_T$ transmit antennas and $N_R$ ($N_T \leq N_R$) receive antennas. At the transmitter, information bit streams are coded, interleaved, and mapped to symbols, the symbols are then fed to $N_T$ transmit antennas by serial-to-parallel conversion [1, 2, 3]. The received signal vector $r = [r_1, \ldots, r_{N_R}]^T$ is $r = Hx + w$, where $H$ is an $N_R \times N_T$ channel matrix with its entries $h_{i,j}$ ($i = 1, \ldots, N_R$, $j = 1, \ldots, N_T$) modeled as independent identically distributed (i.i.d.) circularly symmetric complex Gaussian (CSCG) variables with zero-mean and variance $\sigma^2_h$. $x = [x_1, \ldots, x_{N_T}]^T$ is the transmitted symbol vector and its elements are taken from a constellation set $\Omega = \{a_1, \ldots, a_Q\}$ with an average power $\sigma^2_x$, each $x_n$ ($n = 1, \ldots, N_T$) is mapped by $q = \log_2 Q$ bits, i.e., $b_{n,j}$, $j = 1, \ldots, q$. $w = [w_1, \ldots, w_{N_R}]^T$ is an i.i.d. CSCG noise vector with zero-mean and covariance $\sigma^2_w I_{N_R}$, where $I_{N_R}$ is an $N_R \times N_R$ identity matrix. The signal-to-noise ratio (SNR) is defined as $\frac{\sigma^2_x}{\sigma^2_w}$.

Now let us draw a brief review of the Conv detector [1, 2, 3]. Suppose that at the $k$th ($k = 1, 2, \ldots$) soft interference cancellation (SIC) iteration, we have acquired an estimated mean vector (usually called soft decision vec-
for channel decoding at the $\hat{r}_n$ and perform SIC conditionally on variance CEE matrix with its entries being i.i.d. CSCG variables with zero-mean and variance $\sigma^2_{x_n,k}$. The maximum-likelihood (ML) channel estimation [5] is adopted in this paper.

The estimated channel $\hat{h}_{n,k}$ is obtained as follows:

$$\hat{h}_{n,k} = \frac{\sigma^2_{x_n,k} h_{n,k} (H^T h_{n,k} H + \sigma^2_{\mu,n} I_{N_T})^{-1}}{\sigma^2_{h_n,k}}$$

where $h_{n,k}$ is the $n$th column of $H$, $D_{n,k}$ is the diagonal matrix with $d_{n,k}^2 = [d_{1,k}^2, \ldots, d_{N_T,k}^2]^T$ on its diagonal. The MMSE filtering output can be written as $z_{n,k} = f_{n,k} r_{n,k} + \mu_{n,k} x_n + v_{n,k}$, where $\mu_{n,k} = f_{n,k} h_{n,k}$ is the MMSE filtering bias, $v_{n,k} = \sum_{m \neq n} f_{n,k} h_{m}(x_m - \hat{x}_m,k) + f_{n,k} w$ is the residual interference plus noise item which can be modeled as a complex Gaussian variable with zero-mean and variance $\sigma^2_{v_{n,k}} = \sigma^2_{x_n,k}(1 - \mu_{n,k})$. Defining the soft metric of $x_n$ as $\omega_k(x_n) = \exp(-|z_{n,k} - \mu_{n,k} x_n|/\sigma^2_{v_{n,k}})$, $x_n \in \Omega$, the extrinsic information of $b_{n,j}$ ($j = 1, \ldots, q$) needed for channel decoding at the $k$th SIC iteration is

$$L_k(b_{n,j}) = \log \frac{\sum_{x_n \in \Omega} \omega_k(x_n) \text{apriori}(x_n)}{\sum_{x_n \in \Omega} \omega_k(x_n) \text{apriori}(x_n)} - \log \frac{\text{apriori}(b_{n,j} = +1)}{\text{apriori}(b_{n,j} = -1)}$$

where $x_n = \{\Omega|b_{n,j} = +1\}$, $x_n = \{\Omega|b_{n,j} = -1\}$, $\text{apriori}(\cdot)$ is the a priori probability which can be calculated with channel decoding outputs at the $(k-1)$th SIC iteration.

3 Modified ISIC-MMSE detector with estimated CSI

The maximum-likelihood (ML) channel estimation [5] is adopted in this paper. In one burst, the received pilot block can be written as $Y = HS + Z$, where $Y$ and $Z$ are the $N_R \times L_p$ received signal matrix and noise matrix, respectively, $S$ is the $N_T \times L_p$ FFT orthogonal pilot matrix whose entries have the same power as the data symbols, i.e., $\sigma^2_p = \sigma^2_{x_n,k}$ [5]. The estimated channel matrix is $\hat{H} = Y S^H (S S^H)^{-1} = \hat{H} + \Psi$, where $\Psi = Z S^H (S S^H)^{-1}$ is the CEE matrix with its entries being i.i.d. CSCG variables with zero-mean and variance $\sigma^2_{\psi} = \sigma^2_{x_n,k}/(\sigma^2_{L_p})$ [5]. The $m$th columns of $\hat{H}$ and $\Psi$ are denoted as $\hat{h}_m$ and $\psi_m$, respectively.

Now we are ready to derive the Mod detector. Defining $\eta = \sigma^2_{\psi}/\sigma^2_{h}$, $\alpha = 1/(1+\eta)$, $\beta = \eta/(1+\eta)$, $\gamma = \sigma^2_{h}/(1+\eta)$, then, based on conditional probability theory [6] and note that $h_m$ and $\psi_m$ are independent of $\hat{h}_m$ for $m \neq n$, we have

$$E(h_m H) = \alpha \hat{h}_m, E(\psi_m H) = \beta \hat{h}_m, E(h_m h_m^T | \hat{H}) = \gamma I_{N_R} + \alpha^2 \hat{h}_m \hat{h}_m^T, E(\psi_m \psi_m^T | \hat{H}) = \gamma I_{N_R} + \beta^2 \hat{h}_m \hat{h}_m^T.$$
mean vector with correlation matrix

\[
R_{w_1} = E(w_1 w_1^H | \hat{H}) = \sum_{m \neq n} |\hat{h}_m d_{m,k}^2 \hat{h}_m - 2\beta_0 \hat{h}_m d_{m,k}^2 \hat{h}_m + \beta_0^2 \hat{h}_m d_{m,k}^2 \hat{h}_m + \gamma (d_{m,k}^2 + |\bar{x}_{m,k}|^2) I_{NR}|
\]

Conditionally on \( \hat{H} \), the MMSE filtering vector \( \tilde{f}_{n,k} \) that minimizes \( E[|x_n - \tilde{f}_{n,k} \tilde{r}_{n,k}|^2 | \hat{H}] \) can be derived based on orthogonality principle as

\[
\tilde{f}_{n,k} = E(x_n \tilde{r}_{n,k}^H | \hat{H}) E(\tilde{r}_{n,k} \tilde{r}_{n,k}^H | \hat{H})^{-1}
\]

The MMSE filtering output will be \( \tilde{z}_{n,k} = \tilde{f}_{n,k} \hat{h}_n x_n + \tilde{f}_{n,k} (w_1 + w) \), where \( \tilde{f}_{n,k} (w_1 + w) \) is the residual interference plus noise item at the MMSE filtering output. Note that conditionally on \( \hat{H} \), \( \tilde{f}_{n,k} (w_1 + w) \) is a zero-mean variable, then the conditional mean and variance of \( \tilde{z}_{n,k} \) are calculated respectively as follows

\[
\varepsilon_{\tilde{z}_{n,k}} = E(\tilde{z}_{n,k} | \hat{H}) = \alpha \tilde{f}_{n,k} \hat{h}_n x_n
\]

\[
\sigma^2_{\tilde{z}_{n,k}} = E(\tilde{z}_{n,k} \tilde{z}_{n,k}^H | \hat{H}) - E_{\tilde{z}_{n,k}} E_{\tilde{z}_{n,k}}^H
\]

where \( \tilde{h}_{n,k} = \tilde{f}_{n,k} \hat{h}_n \). By modeling \( \tilde{z}_{n,k} \) as a complex Gaussian variable, we can calculate the soft metric of \( x_n \) at the \( k \)th SIC iteration as

\[
\tilde{\omega}_k(x_n) = (1/\sigma^2_{\tilde{z}_{n,k}}) \exp(-|\tilde{z}_{n,k} - \alpha \tilde{f}_{n,k} \hat{h}_n x_n|^2/\sigma^2_{\tilde{z}_{n,k}}), \quad x_n \in \Omega
\]

The extrinsic information needed for channel decoding is still calculated with Eq. (1) except that \( \omega_k(x_n) \) is replaced by \( \tilde{\omega}_k(x_n) \). From the above derivation, it is clear that the Mod detector will degrade to the Conv detector as the CEE vanishes. Note that the Mod detector additionally needs the knowledge of \( \sigma^2_h \), under the assumption that \( \sigma^2_w \) is known at the receiver, we first estimate the variance of the entries of \( \hat{H} \) as \( \sigma^2_h = (\sum_{i=1}^{N_h} \sum_{j=1}^{N_T} |\hat{h}_{i,j}|^2)/(N_R N_T) \), where \( \hat{h}_{i,j} \) is the \((i, j)\)th entry of \( \hat{H} \). Then, based on the independence between \( \hat{H} \) and \( \Psi \), we obtain the estimate of \( \sigma^2_h \) as \( \hat{\sigma}^2_h = \sigma^2_h - \sigma^2_w \).

The complexities of both the Conv and the Mod detectors are dominated by the MMSE filtering calculations. By taking advantage of the Hermitian
property of the matrix to be inversed in Eq. (4), the MMSE filtering calculation (i.e., Eq. (4)) has a complexity of $O(N_T N_R^2)$ for detecting $x$ at each SIC iteration [7], which is the same as in the Conv detector. The additional calculations introduced by the Mod detector (mainly lie in calculating Eq. (4) and Eq. (6)) have a complexity of $O(N_T N_R)$ at each SIC iteration, also note that estimating $\sigma_h^2$ needs to be performed just once in each burst, therefore, the complexity increase introduced by the Mod detector is only moderate as compared with the Conv detector.

4 Simulation results

We consider a BICM SM-MIMO system with $N_T = N_R = 8$ and Gray mapped QPSK and 16QAM modulations. We adopt a rate-1/2 (7,5) turbo code and a BCJR decoding with 8 decoding iterations. Random interleaving is used for both turbo code interleaving and channel interleaving. $L_d$ is set to 50 in each burst, each turbo coding block occupies one burst and each channel interleave block contains one coding block. $\sigma_w^2$ is assumed to be known at the receiver, and $\sigma_h^2$ is estimated with the method in Section 3. In all figures, $2 \times 10^6$ randomly generated channel realizations are tested for each SNR value. Fig. 1 (a) and Fig. 1 (b) show the performances of the Conv and the Mod detectors with $L_p = 20$ at $k=1,2,3,4$ SIC iterations for QPSK and 16QAM modulations, respectively. We see that the Mod detector can obtain considerable performance advantage over the Conv detector. Fig. 2 (a) and Fig. 2 (b) show the performances of the Conv and the Mod detectors with $L_p = 10,15,20$ at $k=4$ SIC iteration for QPSK and 16QAM modulations, respectively. We see that compared with the Conv detector, the Mod detector needs a smaller $L_p$ to acquire the same performance, which indicates that transmission rate gains can be obtained by the Mod detector.

Fig. 1. Performance comparison between the proposed Mod ISIC-MMSE detector and the Conv ISIC-MMSE detector, $L_p = 20$, $k=1,2,3,4$. 
Fig. 2. Performance comparison between the proposed Mod ISIC-MMSE detector and the Conv ISIC-MMSE detector, \(k=4, L_p = 10, 15, 20\).

5 Conclusion

Owing to its making a good tradeoff between performance and complexity, the ISIC-MMSE detector has become a popular detector for MIMO systems with large constellations and a large number of antennas. The Conv detector proposed in [1, 2, 3] is based on ideal CSI; however, due to the fact that CEE can not be avoided, the Conv detector suffers from performance loss in practical systems. In this paper, by redesigning all the three modules of the ISIC-MMSE detector based on estimated CSI, we have proposed a Mod detector to reduce the performance loss introduced by CEE. Simulation results demonstrate that the Mod detector can considerably outperform the Conv detector in terms of performance and transmission rate with only moderate complexity increase, which facilitates the application of the Mod detector in practical systems. Finally, we note that the Mod detector is also applicable to space division multiple access (SDMA) MIMO systems in which channel coding/decoding of different data streams (from different user equipments) are performed separately.

Acknowledgments

This work is supported by NSFC (61072070), 863 Program (2009AA01Z237), Major National Science & Technology Projects (2009ZX03003-005, 2010ZX03 006-002-04), PCSIRT (IRT0852), 111 Project (B08038), Fundamental Research Funds for Central Universities (K50510010013), and Research Funds of ISN Laboratory (ISN1003005).