BLIND LAYERED SPACE-TIME EQUALIZATION FOR MIMO OFDM SYSTEMS

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ABSTRACT

This paper proposes a novel blind receiver for multiple-input multiple-output (MIMO) orthogonal frequency division multiplexing (OFDM) systems, where blind source separation (BSS) and V-BLAST are combined to perform layered space-time equalization without training sequences. It is shown that the proposed system significantly improves the performance compared to using BSS only and can approach the performance with perfect channel state information (CSI).

1. INTRODUCTION

The multiple-input multiple-output (MIMO) technique has been proposed to increase the data rate for wireless communications [1, 2] by transmitting data in parallel streams. The vertical Bell Laboratories Layered Space-Time (V-BLAST) structure [3] is an effective receiver for MIMO systems using successive interference cancellation, where the previously detected data streams are removed from the received signals. It has been applied to MIMO orthogonal frequency division multiplexing (OFDM) systems in [4]. The use of OFDM for MIMO systems is motivated by its low transceiver complexity and simple equalization in frequency selective environments.

Blind source separation (BSS) allows the recovery of the transmitted streams from the observed mixtures only based on the assumption of independence between the streams [5]. This increases the bandwidth efficiency of the system since no training data or pilot tones are necessary for channel estimation. In [6] a blind receiver for MIMO OFDM systems based on BSS was presented.

In this paper we combine the layered space-time architecture of V-BLAST with BSS to perform blind layered space-time equalization (LSTE) for MIMO OFDM systems. First the channel estimate in each subcarrier is initialised with BSS and then signal detection with V-BLAST is carried out. The order and scaling indeterminacies inherent in BSS methods are handled in the final step. Our work is different from the single carrier system in [7] in that we employ OFDM and thus have to consider the order and scaling indeterminacies of BSS in each subcarrier. Simulations with Rayleigh block fading channels show considerable performance improvement over using BSS only. Furthermore, the performance can approach the ideal case with perfect channel state information (CSI) at the receiver.

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2. SIGNAL MODEL

In the proposed system, N_t transmit and N_r receive antennae are used. All transmit antennae emit OFDM modulated signals at the same time and on the same frequency band. The transmitted signals are assumed to be mutually statistically independent. Relying on the cyclic prefix OFDM (CP-OFDM) property of transforming a frequency selective channel into parallel flat fading channels [8] and employing at least as many receive as transmit antennae ($N_r \geq N_t$), BSS methods for instantaneous linear mixtures can be employed at the receiver to recover the transmitted source signals [9]. In the following we use a frequency domain signal representation from the subcarrier point of view. After removal of the CP and discrete Fourier transformation (DFT) the i-th received OFDM symbol vector $\mathbf{x}(k,i) = [x_1(k+iN), x_2(k+iN), \cdots, x_{N_r}(k+iN)]^T$ on subcarrier k is

$$\mathbf{x}(k,i) = \mathbf{H}(k)\mathbf{s}(k,i) + \mathbf{n}(k,i) \tag{1}$$

where $x_v(\cdot)$ is the signal received by antenna v, N is the number of subcarriers, $\mathbf{H}(k)$ is the channel matrix of size $(N_r \times N_t)$ which collects the gains of all channels of subcarrier k, $\mathbf{s}(k,i) = [s_1(k+iN), s_2(k+iN), \cdots, s_{N_t}(k+iN)]^T$ is the signal vector transmitted on subcarrier k and $\mathbf{n}(k,i)$ is the additive white gaussian noise (AWGN) vector with zero mean and variance σ^2. The data stream $s_u(\cdot)$ transmitted by antenna u is generated by prefiltering the source data $d_u(\cdot)$ with an FIR prefilter $c(l)$ to allow reordering and scaling of the detected streams at the receiver based on correlation between neighbouring subcarriers [9]. This is necessary due to the order and scaling indeterminacy of BSS methods [5].

$$s_u(k+iN) = \sum_{l=0}^{F-1} c(l)\, d_u(k+iN-l) \tag{2}$$

The following prefilter with complex valued impulse response

$$c(l) = \begin{cases} 1/\sqrt{2} & (l=0) \\ j/\sqrt{2} & (l=1) \end{cases} \tag{3}$$

and length $F = 2$ is used so that $s_u(\cdot)$ has a QPSK constellation when BPSK source data $d_u(\cdot)$ is used. The source data $d_u(\cdot)$ is assumed to have unit variance. Note that the prefiltering does not increase the signal power.

3. BLIND LAYERED SPACE-TIME EQUALIZATION

3.1 Overview

The proposed blind receiver for MIMO OFDM uses a combination of BSS and V-BLAST to recover QPSK streams up

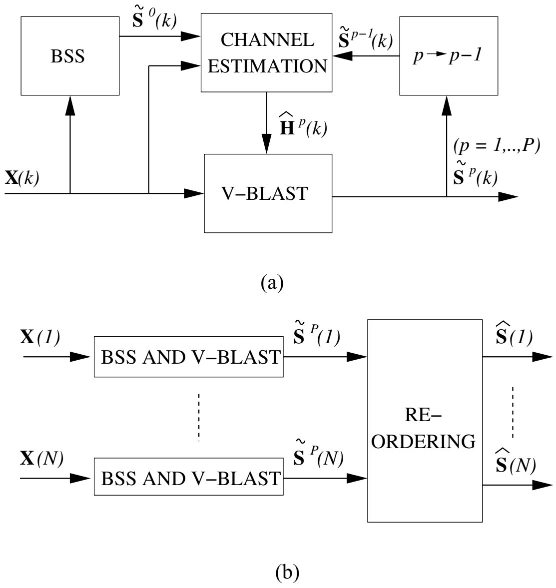

Figure 1: (a) BSS and V-BLAST in each subcarrier k, (b) Overall blind LSTE receiver structure with reordering and P iterations

to a phase shift and stream ambiguity. The system operates block wise and uses the following three steps:

1. Initialise the channel estimation with BSS in each subcarrier.
2. Estimate the data streams with V-BLAST in each subcarrier, using the estimated channel knowledge. The output signals are then used to update the channel estimate. This step can be reiterated to improve the performance.
3. Reorder and phase shift the recovered streams to obtain the same order and phase shift for each stream across all subcarriers.

Fig. 1(a) shows the BSS and V-BLAST steps used in each subcarrier and Fig. 1(b) shows the overall LSTE receiver structure with the reordering, which is common to all subcarriers. The blocked received signal is

$$\mathbf{X}(k) = [\mathbf{x}(k,1), \mathbf{x}(k,2), \cdots, \mathbf{x}(k,N_s)] \qquad (4)$$

where N_s is the block size, which corresponds to the number of transmitted vectors. The blocked tentative data estimate at iteration p is

$$\widetilde{\mathbf{S}}^p(k) = [\tilde{\mathbf{s}}^p(k,1), \tilde{\mathbf{s}}^p(k,2), \cdots, \tilde{\mathbf{s}}^p(k,N_s)] \qquad (5)$$

with $p = 1, \cdots, P$ where P is the number of iterations of V-BLAST and $\widehat{\mathbf{H}}^p(k)$ is the MIMO channel estimate at iteration p. The final reordered and phase corrected estimate of the blocked transmitted data $\mathbf{S}(k) = [\mathbf{s}(k,1), \mathbf{s}(k,2), \cdots, \mathbf{s}(k,N_s)]$ is given by

$$\widehat{\mathbf{S}}(k) = [\hat{\mathbf{s}}(k,1), \hat{\mathbf{s}}(k,2), \cdots, \hat{\mathbf{s}}(k,N_s)]. \qquad (6)$$

3.2 Blind Source Separation

The BSS step employs the JADE [10] method, which uses a two stage approach where first an $(N_t \times N_r)$ whitening matrix $\mathbf{W}(k)$ is obtained so that

$$\mathbf{W}(k) \mathop{\mathrm{E}}_i\{\mathbf{x}(k,i)\mathbf{x}^H(k,i)\}\mathbf{W}^H(k) = \mathbf{I}. \qquad (7)$$

Here $\mathop{\mathrm{E}}_i\{\cdot\}$ denotes the expectation with respect to i, $(\cdot)^H$ is the Hermitian transpose and $\mathbf{I}$ is the $(N_t \times N_t)$ identity matrix. This step, which is also referred to as principal component analysis (PCA), performs a dimension reduction if $N_r > N_t$. The second stage uses fourth order cumulants to obtain a unitary $(N_t \times N_t)$ matrix $\mathbf{V}(k)$ such that the entries of $\tilde{\mathbf{s}}^0(k) = \mathbf{V}^H(k)\mathbf{W}(k)\mathbf{x}(k)$ recover the independent streams. $\mathbf{V}(k)$ is the maximiser of

$$c[\mathbf{V}(k)] = \sum_{q,r,t=1}^{N_t} \left|\mathrm{Cum}\left[\tilde{s}_q^0(k), \tilde{s}_q^{0*}(k), \tilde{s}_r^0(k), \tilde{s}_t^{0*}(k)\right]\right|^2 \qquad (8)$$

with $\mathrm{Cum}(\cdot)$ being the 4-th order cumulant and $(\cdot)^*$ the complex conjugate. The index i has been dropped here to simplify notation. The order and scaling ambiguity of BSS methods [5] is handled in the last step.

3.3 Channel Estimation and V-BLAST

First, the channel estimate for the p-th iteration is obtained:

$$\widehat{\mathbf{H}}^p(k) = \begin{cases} \mathbf{X}(k)\mathrm{Q}^+[\widetilde{\mathbf{S}}^0(k)] & (p=1) \\ \mathbf{X}(k)[\widetilde{\mathbf{S}}^{p-1}(k)]^+ & (p>1) \end{cases} \qquad (9)$$

where $(\cdot)^+$ denotes the pseudo-inverse and $\mathrm{Q}[\cdot]$ denotes the hard estimation function for QPSK, which will be defined later. The V-BLAST step can be re-iterated ($p > 1$), which results in a new channel estimate obtained from the V-BLAST output $\widetilde{\mathbf{S}}^{p-1}(k)$ instead of the BSS output $\widetilde{\mathbf{S}}^0(k)$ as depicted in Fig. 1(a).

Using the channel estimate $\widehat{\mathbf{H}}^p(k)$, a V-BLAST scheme [3] is employed to obtain a refined soft estimate of the streams

$$\tilde{s}_u^p(k+iN) = \mathbf{w}_u^{pH}(k)\mathbf{x}(k,i) \qquad (10)$$

which are passed on to the decision device $\mathrm{Q}[\cdot]$ to obtain the hard estimates $\check{s}_u^p(k+iN) = \mathrm{Q}[\tilde{s}_u^p(k+iN)]$. In (10) $\mathbf{w}_u^p$ is the minimum mean square error (MMSE) equalizer vector for stream $u \in \{1, 2, \cdots, N_t\}$ given by

$$\mathbf{w}_u^p(k) = [\mathbf{R}_u^p(k)]^{-1}\,\hat{\mathbf{h}}_u^p(k). \qquad (11)$$

The autocorrelation matrix is

$$\mathbf{R}_u^p(k) = \left[\sum_n \hat{\mathbf{h}}_n^p(k)\hat{\mathbf{h}}_n^{pH}(k) + \sigma^2\mathbf{I}\right] \qquad (12)$$

with the summation over all the undetected streams and $\hat{\mathbf{h}}_u^p(k)$ is column u of $\widehat{\mathbf{H}}^p(k)$.

The hard estimation function $\mathrm{Q}[\cdot]$ performs derotation and hard estimation of QPSK unit variance symbols. Derotation is necessary due to the scaling ambiguity of BSS which leads to an arbitrary phase shift of the recovered streams. The scalar derotation factor $\alpha_u^p \in \mathbb{C}$ is determined for QPSK by $\alpha_u^p = \mathop{\mathrm{E}}_i\{[\tilde{s}_u^p(k+iN)]^4\}^{-\frac{1}{4}}e^{j\frac{\pi}{4}}$ [7]. Note that after derotation a quadrant ambiguity remains. The reordering step at the end will ensure the same phase shift across all subcarriers.

The streams $\tilde{s}_u^p(\cdot)$ are extracted recursively ordered from lowest to highest post-detection mean square error (MSE)

$$MSE_u^p(k) = 1 - \hat{\mathbf{h}}_u^{pH}(k)[\mathbf{R}_u^p(k)]^{-1}\hat{\mathbf{h}}_u^p(k). \qquad (13)$$

Next, the interference of this extracted stream is removed from the received signals to obtain an updated received signal vector for the extraction of the next stream

$$\mathbf{x}(k,i) = \mathbf{x}(k,i) - (\alpha_u^p)^{-1}\hat{\mathbf{h}}_u^p(k)\tilde{s}_u^p(k+iN). \qquad (14)$$

The derotation applied for hard estimation has to be considered here to cancel the interference of the stream $\tilde{s}_u^p(\cdot)$ correctly.

3.4 Reordering

In the last step, the estimated streams $\tilde{s}_u^P(k+iN)$ are reordered and phase shifted to obtain the same order and phase shift for each stream across all subcarriers k. This means that the reordering obtains the same stream index u and phase shift across all subcarriers for data belonging to the same stream. The reordering method in [6] relies on the fact that, due to prefiltering with $c(l)$, data in neighbouring subcarriers is correlated if it belongs to the same stream. It is extended here to $N_t > 2$ and complex valued prefilters $c(l) \in \mathbb{C}$. In the following, the notation in [11] is used. Precisely, reordering is done by finding the permutation $\pi_k : \{1,2,\cdots,N_t\} \rightarrow \{1,2,\cdots,N_t\}$ in subcarrier k which minimises the sum of squared errors between the cross correlation of neighbouring subcarriers of the detected streams $\rho(\cdot)$ and the known true cross correlation γ

$$\pi_k = \min_{\pi} \sum_{q=1}^{N_t} \left[|\rho(q,k,\pi)| - |\gamma|\right]^2 \qquad (15)$$

with $\rho(q,k,\pi) = \operatorname*{E}_i\left[\tilde{s}^P_{\pi(q)}(k+iN)\,\tilde{s}^{P*}_{\pi_{k-1}(q)}(k-1+iN)\right]$ and π_{k-1} the permutation in the previous subcarrier. The true cross correlation is $\gamma = \operatorname*{E}_i\left[s_u(k+iN)s_u^*(k-1+iN)\right]$. Next, the estimated transmit data vector $\hat{\mathbf{s}}(k,i)$ is obtained by reordering and phase shifting the streams $\tilde{s}_u^P(k+iN)$ in each subcarrier k according to

$$\hat{\mathbf{s}}(k,i) = \mathbf{D}^{-1}\left[\tilde{s}^P_{\pi_k(1)}(k+iN),\cdots,\tilde{s}^P_{\pi_k(N_t)}(k+iN)\right]^T. \qquad (16)$$

The streams are phase shifted by the diagonal matrix $\mathbf{D} = \lfloor \gamma^{-1}\mathrm{diag}\{\rho(1,k,\pi_k),\cdots,\rho(N_t,k,\pi_k)\}\rceil$, where $\lfloor\cdot\rceil$ is the hard estimation function for the rotation factors, which can assume the discrete values $\{e^{j0}, e^{j\pi/2}, e^{j\pi}, e^{j3/4\pi}\}$ only.

The estimate of the transmitted data $\widehat{\mathbf{S}}(k)$ recovers the true data streams up to an inconsequential overall phase shift and stream ambiguity, which is common to all blind detection methods.

4. SIMULATIONS

Simulations were carried out for an $N_t = N_r = 4$ MIMO OFDM system employing $N = 32$ subcarriers and a CP length of $L = 4$. Third order channels with Rayleigh block fading and equal power in all paths were used. This corresponds to an RMS delay spread of 1.1, normalised to the symbol period. The signal to noise ratio (SNR) is defined as the spatial average across all receive antennae. The simulation results averaged over all streams $s_u(\cdot)$ for 1000 Monte-Carlo runs are presented.

Fig. 2 was obtained with a block size of $N_s = 200$. The use of BSS combined with V-BLAST significantly reduces

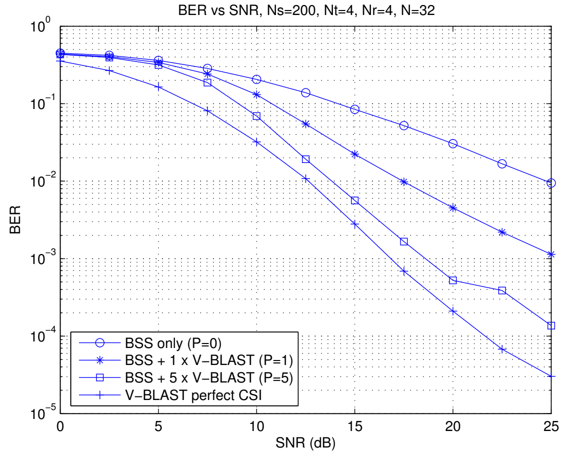

Figure 2: BER vs SNR for $N_s = 200$, $N_t = 4$, $N_r = 4$, $N = 32$

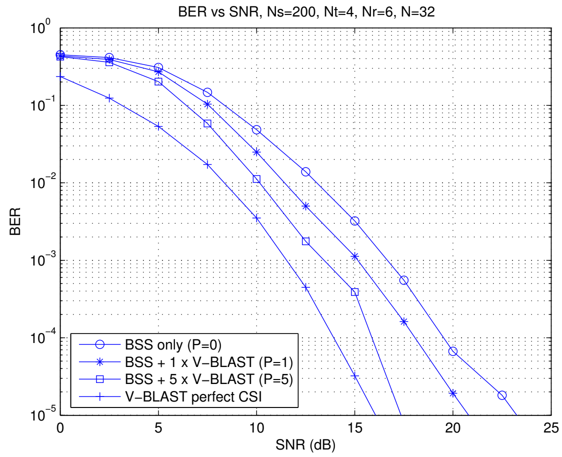

Figure 3: BER vs SNR for $N_s = 200$, $N_t = 4$, $N_r = 6$, $N = 32$

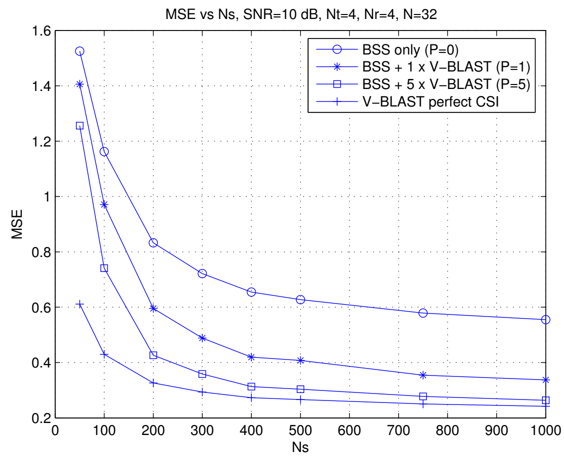

Figure 4: MSE vs N_s for SNR = 10 dB, $N_t = 4$, $N_r = 4$, $N = 32$

Table 1: Analytical computational complexity

	BSS only ($P=0$)	BSS + P x V-BLAST
BSS (JADE)	$N(N_r^2 N_s + N_t^4 N_s + N_t^5)$	
Channel Estimation and V-BLAST	0	$PN[N_s(N_t^2 + N_t N_r) + N_t^3 N_r + N_t N_r^3 + N_t^2 N_r^2]$
Reordering	$N N_s N_t^2 (1 + N_t!)$	

Table 2: Normalised computational complexity with $N_s = 200$, $N = 32$, $N_t = N_r = 4$

BSS only ($P=0$)	BSS + 1 x V-BLAST ($P=1$)	BSS + 5 x V-BLAST ($P=5$)
100 %	105 %	126 %

the bit error rate (BER) compared to the BSS only method in [6]. The combined BSS and V-BLAST method with $P=5$ iterations obtains for instance a gain of 6 dB at SNR = 10 dB. For SNR $>$ 10 dB, the BER using the combined BSS and V-BLAST method approaches the ideal case with V-BLAST and perfect CSI. The benefits from re-iterating V-BLAST can also be observed. Repeating V-BLAST reduces the BER by estimating the channel more accurately. The results illustrate that V-BLAST with blind channel estimation is a viable alternative to V-BLAST with training based channel estimation.

Fig. 3 highlights the benefit of using more receive than transmit antennae. As expected, all methods perform better than in the $N_t = N_r = 4$ case due to the increased diversity. Also, the performance gaps between the methods are reduced.

Next, the influence of the block size N_s on the MSE between the soft estimated streams $\bar{\mathbf{S}}(k)$ and the transmitted streams $\mathbf{S}(k)$ was studied. The MSE was averaged over all streams and subcarriers.

$$MSE = \frac{1}{N_t N N_s} \mathrm{E}\left[\sum_{k=1}^{N} ||\bar{\mathbf{S}}(k) - \mathbf{S}(k)||^2\right] \qquad (17)$$

Here $\bar{\mathbf{S}}(k)$ is built from $\bar{s}_u^P(k+iN)$ in the same way as $\mathbf{S}(k)$ from $s_u(k+iN)$ and $||\cdot||$ denotes the Frobenius-norm. Fig. 4 shows the MSE at 10 dB SNR. It can be seen that the lower bound of the MSE is approached with a block size of only $N_s = 200$. Note that in order to calculate the MSE, the rows of the estimated data $\bar{\mathbf{S}}(k)$ have to be reordered and phase shifted as the true data $\mathbf{S}(k)$ beforehand.

5. COMPLEXITY ANALYSIS

Table 1 compares the proposed receiver and the BSS only method in [6] in terms of the order of the analytical computational complexity where one unit corresponds to a complex valued floating point multiplication and addition. The relative computational complexity in Table 2 was obtained with the parameters as defined above. It demonstrates that the proposed receiver with V-BLAST and BSS entails only a moderate increase in computational complexity compared to the BSS only approach, while outperforming it by a considerable margin as evidenced by simulations in Section 4.

6. CONCLUSION

A blind receiver for MIMO OFDM has been presented. Using BSS combined with V-BLAST the performance of the proposed blind LSTE receiver has been significantly improved compared to using BSS only. The performance gain comes at a moderate increase of computational complexity. It has been shown that the performance can approach the ideal case when perfect CSI is available, making it a viable alternative to a training based system.

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