Turbo-BLAST with Semi-Blind Co-Channel Interference Cancellation in Multicell MIMO Systems

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***Abstract*— Multicell MIMO is typically interference-limited. Advanced signal-processing techniques like multiuser detection can be exploited to effectively combat co-channel interference and significantly improve system performance, provided perfect information for interferers is available. This consumes substantial amount of scarce system resource and may be difficult to obtain in practice. In this paper we first exploit the turbo principle to enhance an effective blind detection method based on multiuser kurtosis (MUK) maximization, thus coined as turbo-MUK. In turbo-MUK a few training symbols are needed to resolve the possible phase and ordering ambiguity, making it a semi-blind method. Then we propose a multi-cell MIMO receiver structure that employs turbo-BLAST to detect the desired signal and turbo-MUK to deal with interference, and iterates between the two in a group multistage detection fashion to further improve the performance. Simulation results indicate that our newly proposed technique achieves satisfactory performance, while significantly reduces the associated system overhead.**

Keywords-blind detection, multicell MIMO, turbo principle.

I. INTRODUCTION

It has been shown that the spectral efficiency of multiple-input multiple-output (MIMO) systems grows at least linearly with the minimum of the number of transmit and receive antennas [1][2], when operating on a single link with white Gaussian noise. However, in a cellular environment, co-channel interference (CCI) becomes dominating channel impairment and the capacity of a MIMO system is hardly larger than when using multiple antennas at receiver only [3]. In a recent work [4], several multiuser detection techniques (such as linear MMSE and group interference cancellation) have been explored to combat CCI and significantly improve the performance of MIMO systems in a multicell structure. But, these advanced signal-processing schemes assume availability of perfect channel state information (CSI) for the interferers at the receiver, which consumes significant amount of system resources and is difficult to obtain in some circumstances. There are various blind detection methods in literature which may find applications in this scenario. Among these, one based on multi-user kurtosis (MUK) maximization [7] is particularly attractive due to its low complexity and globally convergent behavior. Motivated by the turbo-BLAST structure proposed in [4], we propose an analogous space-time detection structure (named as turbo-MUK), which consists of an MUK parallel interference cancellation (PIC) stage and a soft-input soft-output decoder stage, and exploits the turbo principle for performance enhancement. The turbo-MUK scheme developed here is semi-blind in nature as a few training symbols are needed to resolve the possible phase and ordering ambiguity inherent to any blind detection methods. Further, we propose a new receiver structure for MIMO systems in a cellular environment. This receiver structure employs turbo-MUK to detect strong interfering signals (and removes them so as to assist the detection of the desired signal), which being semi-blind in nature results in much lower system overhead. The desired signal is detected using turbo-BLAST and a group multistage interference cancellation structure is exploited to further improve the performance.

The rest of this paper is organized as follows. Section II gives the system model. Section III presents a brief description of the original MUK method and continues with a discussion of the turbo-MUK scheme proposed. In Section IV a novel receiver structure for MIMO systems in a cellular environment is illustrated, employing turbo-MUK for semi-blind interference cancellation. Simulation results are given in Section V. Section VI contains concluding remarks and directions for future work.

II. SYSTEM MODEL

Consider a multicell MIMO system, where each cell has a transmitter with N_T antennas and a receiver with N_R antennas forming an $N_R \times N_T$ MIMO system. We take into account interference from the first tier of centre-excited cell configuration with a reuse factor of one, and assume a frequency-flat quasi-static fading environment. The multicell system model is given by

$$Y = HX + \sum_i H_{ifi} X_{ifi} + N \, , \tag{1}$$

where the subscript 'if' denotes interference. H and H_{ifi} are the channel matrices that capture the channel characteristics between the receiver in the cell of interest and the transmitter in the same cell, and the transmitter in the i^{th} interfering cell, respectively. These channel matrices H and $\{H_{ifi}\}$ are independent of each other, with independent and identically distributed (i.i.d.) normalized complex Gaussian entries, modeling the multipath Rayleigh fading. X and X_{ifi} are the transmitted signal vectors for the desired user and the i^{th} interfering user, respectively, with power constraints $E[X^H X] \le P$ and $E[X_{ifi}{}^H X_{ifi}] \le P_{ifi}$, which include the path loss factor. The background noise vector N is circularly symmetric Gaussian with covariance matrix $\Phi_N = \sigma^2 I$. The signal to noise ratio (SNR) is given by $\rho = P / \sigma^2$ and signal to interference ratio (SIR) is given by $\eta = P / \sum_i P_{ifi}$.

III. TURBO – MUK ALGORITHM

A. Multiuser kurtosis (MUK) maximization criterion

For ease of illustration let us assume a single-cell MIMO

$$Y = HX + N \,. \tag{2}$$

The purpose is to blindly design an $N_R \times N_T$ matrix equalizer W that produces the $N_T \times 1$ output Z when applied to the received signal Y:

$$Z = W^T Y = W^T HX + W^T N = G^T X + N_W \,. \tag{3}$$

A blind recovery of the transmitted signal vector is said to be achieved if the following equation holds (in absence of noise)

$$Z = G^T X = \Phi \Pi X = \begin{bmatrix} e^{i\phi_1} & 0 & .. & 0 \\ 0 & e^{i\phi_2} & .. & 0 \\ .. & .. & .. & .. \\ 0 & 0 & .. & e^{i\phi_{NT}} \end{bmatrix} \Pi X \,, \tag{4}$$

where $\{\phi_1, ..., \phi_{NT}\} \in [0, 2\pi)$ are arbitrary phase terms and Π is an arbitrary permutation matrix. This phase and ordering ambiguity is due to the inability of the statistical blind methods to distinguish between rotated versions of symmetric and identically distributed sources. Assuming zero-mean i.i.d. input sequences which are mutually independent with kurtosis $K_x = E(|x|^4) - 2E^2(|x|^2) - |E(x^2)|^2$ and variance σ_x^2, the necessary and sufficient conditions for blind recovery are given by (1) $K(z_j) = K_x$, $\forall j$; (2) $E\{z_j^2\} = \sigma_x^2$, $\forall j$; (3) $E\{z_k z_l^*\} = 0$, $\forall k \ne l$ [7][8].

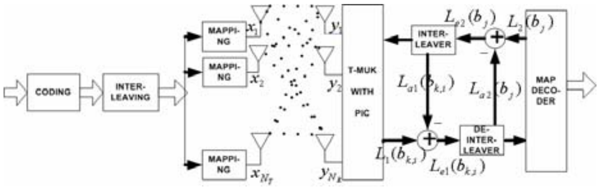

Fig. 1 Structure of turbo-MUK

This set of conditions leads to the MUK maximization criterion for blind source separation given as

$$\max_G F(G) = \sum_{j=1}^{N_T} |K(z_j)|$$

$$subject\ \ to: G^H G = I_{NT} \,. \tag{5}$$

Adaptive methods (like stochastic gradient descent) can be used to solve the optimization problem above and compute the equalizer matrix W. To this end, it is advantageous if the channel matrix H is made unitary, so that the constrained optimization problem can be directly expressed and solved with respect to W. Such channel whitening can be achieved in the following way. Ideally eigenvalue decomposition (EVD) of the receive covariance matrix $R_{YY} = \sigma_x^2 HH^H = LDL^H$ yields a matrix $\tilde{L}$ that contains the non-zero part of $LD^{1/2}$. It is fairly obvious that if we pre-filter the received signal vector with the pseudo-inverse of $\tilde{L}$ (denoted as P) then we effectively whiten the channel matrix. In practice, $\tilde{L}$ can be approximated by truncating the N_T largest eigenmodes in the EVD of the estimated receive covariance matrix $\hat{R}_{YY}$. Note that there are a few other advantages of channel whitening. First, lower complexity is achieved due to reduced dimension. Second, the applications of MUK algorithms can be extended to include the case where the sources are independent but not identically distributed. This may arise in a multiuser scenario where different streams assume different power level. Channel whitening reinforces same variances for all streams and validates the MUK criterion. Finally, channel whitening enables MUK algorithms to work in the situation where there is insufficient degrees of freedom (DOF), i.e., more transmitted signals than receive antennas. In this scenario, one has the flexibility to detect some of the stronger signals and ignore others. This property is especially useful in the cellular environment as we discuss below.

B. Turbo - MUK

The proposed turbo-MUK detection structure is depicted in Fig. 1. At the transmitter the information bits are coded and interleaved as a whole, then the whole coded stream is de-multiplexed into N_T sub-streams, which are symbol-mapped individually and transmitted. The receiver comprises a MUK with PIC detection stage and a Max-log-MAP decoder stage. The MUK-PIC detector uses the *a priori* information L_{a1} and the channel output to produce the extrinsic information L_{e1}, which is de-interleaved and becomes *a priori* information L_{a2} for the decoder. The decoder then uses the Max-log-MAP algorithm [9] to produce the extrinsic information L_{e2}, which is interleaved and becomes *a priori* information L_{a1} for the detector stage. After several such iterations involving interchange of soft information about coded bits between the detector and decoder stage, soft estimate at the decoder output becomes good enough to take a hard decision and estimate the transmitted information bits.

The decoder stage has been discussed in detail in literature [9]. However, the detection stage, which is an enhancement on the MUK detector discussed in the preceding section, deserves more description. The main added features are its ability to use soft information from the decoder stage to improve the detection process and to generate soft information at its output. Also, it incorporates parallel interference cancellation, i.e., it tries to cancel out the interference from other streams when detecting a particular data stream.

The detection process starts by pre-whitening the received vector signal to obtain $Y_P = PY$. We then apply the MUK algorithm on the whitened data block $\{Y_P\}$ to the compute equalizer matrix W. As shown earlier in (3) this matrix is used to filter $\{Y_P\}$ and produce the output vector block $\{Z\}$. Noise at the equalizer output is Gaussian distributed with zero mean and covariance matrix $\Phi_{N_W} = W^T PP^H W^* \sigma^2$. At high SNR, the k^{th} component of output is well approximated as

$$z_k = \mu_k x_j + \eta_k \, , \tag{6}$$

where $\mu_k = (G^T)_{kj}$, and η_k is a Gaussian variable with zero mean and variance $\upsilon_k^2 = [\Phi_{N_W}]_{kk}$. Note that z_k is the estimate for some j^{th} substream instead of the k^{th} substream because of the ordering ambiguity. Assume that the permutation matrix Π and phase rotation matrix Φ are known to the receiver, the global response matrix can be approximated as $G^T = \Phi\Pi$ (see (4)). In practice, ordering and phase ambiguity can be removed using a few training symbols. Alternatively, ordering ambiguity can also be resolved through assigning unique spreading sequences to different substreams [11]. Suppose each substream adopts M-QAM at the transmitter, the extrinsic information for the i^{th} bit, $1 \le i \le \log_2 M$, in the k^{th} substream is given by

$$L_{e1}(b_{k,i}) = \log \frac{\sum\limits_{\forall x_j : b_{k,i} = +1} p(z_k \mid x_j) p(x_j)}{\sum\limits_{\forall x_j : b_{k,i} = -1} p(z_k \mid x_j) p(x_j)} - L_{a1}(b_{k,i}) \, , \tag{7}$$

where $p(z_k \mid x_j)$ is Gaussian distributed as indicated above, $p(x_j)$ and $L_{a1}(b_{k,i}) = \log(p(b_{k,i} = 1) / p(b_{k,i} = -1))$ comprise *a priori* information from the decoding stage. After suitable reordering the extrinsic information so produced is multiplexed, de-interleaved and fed as *a priori* information to the decoder stage.

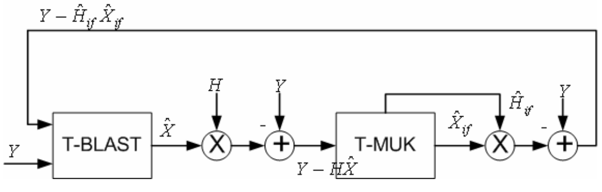

Fig. 2 Structure of semi-blind group IC

The following iterations differ from the first one as interference cancellation is involved. The soft information from the decoder stage is exploited for two additional purposes. First it is used to compute a least square estimate of the channel matrix, $\tilde{H} = Y\tilde{X}^H (\tilde{X}\tilde{X}^H)^{-1}$, (where $\tilde{X}$ is the soft estimate for the transmitted vector signal). Further it is used to reconstruct the interference signals, with which we have for some substream k

$$\tilde{Y}_k = Y - \tilde{H}\tilde{X}_k = HX - \tilde{H}\tilde{X}_k + N \, , \tag{8}$$

where $\tilde{X}_k = [\tilde{x}_1, ...\tilde{x}_{k-1,} \tilde{x}_k = 0, \tilde{x}_{k+1}, ...\tilde{x}_{N_T}]^T$ is the estimated interference vector. At high SNR this interference cancellation will be nearly perfect, so we can perform pre-whitening operation as if there was only one transmitted stream. The pre-whitening transform is a $1 \times N_T$ vector P_k obtained from the strongest eigenmode of the estimated covariance matrix $\hat{R}_{\tilde{Y}_k\tilde{Y}_k}$. The improved estimate for the k^{th} substream $z_k = P_k \tilde{Y}_k$ can again be well approximated in the form of (6) with a different set of mean and variance, given by $\mu_k = P_k \tilde{h}_k$ (where $\tilde{h}_k$ is the k^{th} column of $\tilde{H}$) and $\upsilon_k^2 = P_k P_k^H \sigma^2$. The interference cancellation and whitening procedure is repeated for each of the N_T substreams. Then we compute the extrinsic information using (7) as we did in the first iteration and feed the extrinsic information so obtained to the decoder. The whole procedure is repeated a number of times in order to achieve a good estimate of the transmitted signals.

IV. SEMI – BLIND INTERFERNCE CANCELLATION

Based on the Turbo-MUK algorithm, a new receiver structure is proposed for MIMO systems in a cellular environment. In contrast to traditional single-cell MIMO receivers, it actively combats the CCI in the interference-limited environment. Also different from recent work [4] that assumes perfect CSI for interferers, it is a semi-blind approach which may assume certain advantages in practice. First, it requires far fewer training symbols, which conserves system resource and is especially meaningful for rapidly-changing environment. Furthermore, even if training sequences for interferers are available, much poorer quality is expected for their CSI estimation due to much lower SNR and asynchronism of the signals from the interferers with respect to the desired signals [12].

Our proposed structure assumes a group interference cancellation nature [10][4], as shown in Fig. 2. The detection process is initiated by using turbo-BLAST [4] on the received signal vector Y to get an estimate of the transmitted vector signal $\hat{X}$, which treats any intercell interference as additional noise. Then with the reconstructed desired user's component subtracted from the received signal (assuming perfect channel information H for the desired cell is available), the resultant vector signal is given by

$$Y_{if} = Y - H\hat{X} \, . \tag{9}$$

We then employ turbo–MUK on this vector signal Y_{if} to estimate channel $\hat{H}_{if}$ and transmitted vector signal $\hat{X}_{if}$ for some strongest interfering user(s). With these estimates we attempt to eliminate their detrimental impact from the received vector signal, and feedback a “cleaner” copy to the turbo-BLAST block as

$$Y_S = Y - \hat{H}_{if}\,\hat{X}_{if}\ . \qquad (10)$$

We expect turbo-BLAST to output a better estimate for the transmitted vector signal $\hat{X}$ this time due to reduction in interference power. This iterative procedure is repeated until certain convergence is reached.

Some comments are readily in order. Due to lack of DOF, turbo-MUK can be employed only to deal with some of the strongest interferers. This is realizable with the pre-whitening operation as we mentioned in III. A. This approach actually conforms to our current understanding on the interference channel. As is known, detection of the interfering users is not always optimal except in the strong-interference case, nor is treating them as pure ambient noise optimal, except when they are very weak. As the other side of the same coin, this group IC approach works well at high SNR regimes with sufficient power imbalances among users, and the performance is expected to deteriorate otherwise.

V. SIMULATION RESULTS

First we demonstrate the performance of turbo-MUK for a 6×4 single-cell MIMO. The modulation scheme employed is 4-QAM and the coding scheme used is a rate 1/3 64 state convolutional code with generators $(G_1, G_2, G_3) = (155, 117, 123)_8$. We transmit data blocks of 384 information bits over a frequency-flat, quasi-static fading channel. In our simulations we estimate the arbitrary ordering matrix heuristically as $\Pi = |E[Z^H X]|$, which should approximate the spreading sequence approach in [11]. Meanwhile we use training length of two symbol periods in each block to resolve the phase ambiguity. In Fig. 3 we can observe that at a bit error rate (BER) of 10^{-3}, turbo-MUK gives a gain of over 8 dB over conventional MUK detection in the first iteration itself and another 1.5 dB in subsequent iterations.

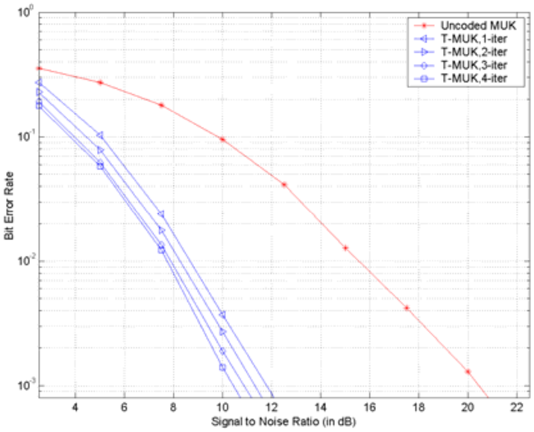

Fig. 3 Performance of turbo-MUK

We continue to justify the effectiveness of the semi-blind group IC scheme proposed in Section IV through numerical results. The modulation scheme, the coding scheme, the data block length and length of training sequence is the same as above. The metric of interest here is the block error probability. We consider a situation where each cell employs a 6×4 MIMO system and there is one dominant MIMO interferer for the desired cell [4]. Fig. 4 depicts the block error rate versus SIR plots for this situation, where the power of the dominant interferer is 6 dB and 9 dB stronger than the sum of the rest. We can see that semi-blind group IC detection offers a gain of about 2 dB and 3 dB as compared to the original turbo-BLAST, which treats CCI as background noise.

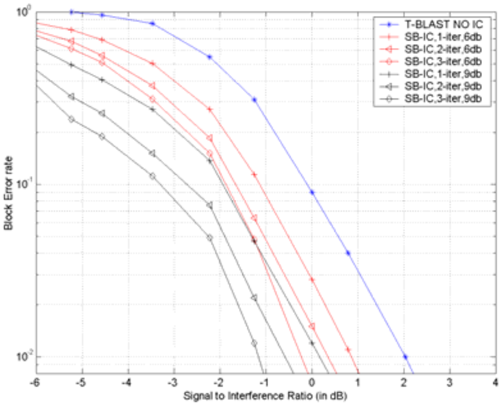

Fig. 4 Performance of semi-blind group IC – One dominant MIMO interferer

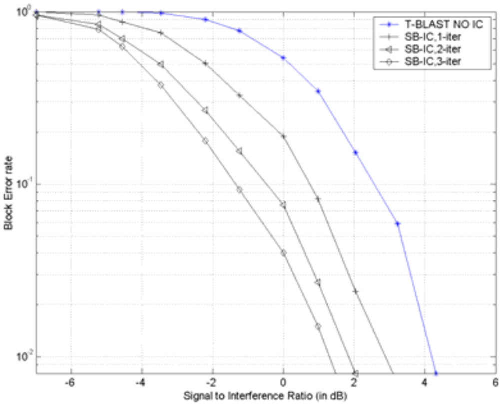

Fig. 5 Performance of semi-blind group IC – Multiple single-antenna interferers

Next, we consider another interesting scenario where the desired cell employs a 4×4 MIMO system while there are some single-antenna interferers around. The differences with the co-located scenario discussed above are that different interfering streams are independently encoded and assume different power. In this example we assume there are four such interferers, with the power level of the strongest one 3 dB stronger than the weakest. From Fig.5, we can observe that semi-blind group IC works well in this situation too, offering a gain of about 3 dB over the original turbo-BLAST. The performance gains in both these situations are achieved without any co-operation between the different users.

Finally, we would like to examine the performance of semi-blind group IC in a severe interference-limited environment. In order to do so we again consider the situations discussed above with the difference that, now we fix SIR and noise floor (at –21db) instead of interference to noise ratio. Fig. 6 shows the block error rate versus SNR plots for the one dominant MIMO interferer scenario (c.f. Fig. 4) where the power of the dominant interferer is 6 dB stronger than the sum of the rest and SIR is fixed at 1 dB. In Fig. 7, we depict the results for the multiple single-antenna interferers scenario with four single antenna interferers in adjacent cells and SIR fixed at 2 dB. Note that semi-blind group IC attains much lower error-floor as compared to the original turbo-BLAST in these interference-limited environments.

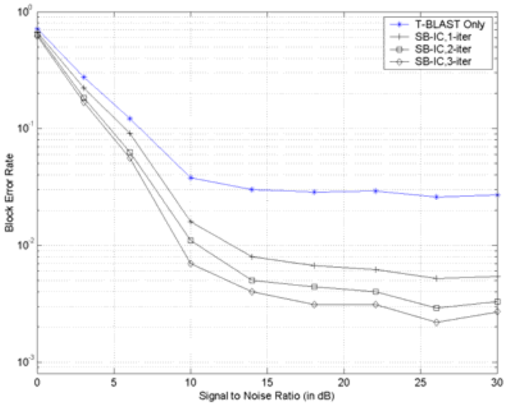

Fig. 6 Performance in interference-limited environment – One dominant MIMO interferer, SIR = 1 dB

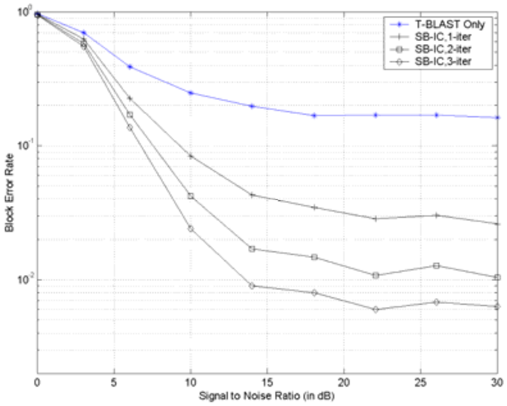

Fig. 7 Performance in interference-limited environment – Multiple single-antenna interferers, SIR = 2 dB

VI. CONCLUSIONS AND FUTURE WORK

In this paper we have developed a semi-blind MUK receiver structure for single cell MIMO communication. Based on it, we also propose a new receiver structure for multicell MIMO communications. Satisfactory performance is observed for various wireless scenarios. These receiver structures could be made completely blind if we can remove the phase ambiguity by incorporating techniques such as rotation invariant convolutional codes or using non-symmetric signal constellations, which constitutes our future work.

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