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# Scheduling schemes with adaptive blind detection for code reuse in multiuser MIMO systems

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## Abstract

To improve spectrum efficiency in wireless multiple-input, multiple-output (MIMO) systems, it is essential to mitigate channel interference. Opportunistic scheduling of multiusers and interference cancellation, such as adaptive multiuser detection, are two commonly used techniques. In this paper, we study the performance improvement of using jointly these techniques to enable the use of the same set of spreading codes to transmit two data streams in closed-loop multiuser MIMO systems. We show that with the proposed scheduling schemes, the performance of an adaptive blind receiver is not degraded when the scheduled users share the same spreading code.

## 1 Introduction

The main obstacle limiting the performance of multiuser multiple-input, multiple-output (MU-MIMO) system and its spectral efficiency is the interference caused by MU-MIMO transmissions that share the same channel [1,2]. To overcome interference, several approaches are currently being implemented, ranging from transmitter adaptation schemes to interference cancellation [3-5]. However, increasing the spectral efficiency is a challenging task when a multiuser interference scenery level is established. Convenient user selection has the potential to efficiently deal with this multiuser interference channel.

An efficient spatial scheduling algorithm is essential to realize the promised benefits of MU-MIMO. So far, many papers have reported practical spatial scheduling schemes to mitigate the residual interference (signal of co-scheduled user), e.g. single antenna at terminals has been widely studied in the last decade [6-8]. In [9], the authors proposed a practical approach for selecting users with orthogonal channel weight vector (CWV). However, that scheme is highly dependent on the availability of a completed CWV at the transmitter side (CWVT) [10]. For practical reasons, a completed CWVT is far from

being realizable, and therefore, strategies based on limited or quantized CWVT have been considered at the expense of degrading received signal quality [10]. However, this performance degradation can be overcome at the receiver side if the detection algorithm, instead of ignoring the residual interference or assuming it to be Gaussian, exploits its structure using interference-aware receivers.

Linear multiuser techniques have been widely analyzed in the literature [11,12]. On MIMO channels, the use of low complexity receivers that improve the performance of the conventional scheme (that treats interference as white Gaussian noise) is of fundamental importance [13,14]. In particular, the adaptive blind receiver (ABR) [15], a blind adaptive version of the minimum-mean-square-error (MMSE) detector, is specially attractive for the downlink MIMO system since, in a dynamic environment, it is very difficult for a mobile user to obtain accurate information on other active users in the channel, such as their spreading code [15]. It is well known that the ABR is based on the minimum output energy (MOE) criterion which searches the component of the desired signal that lies in a subspace orthogonal to the subspace spanned by the interference and noise simultaneously [12]. With this in mind, a careful selection of co-scheduled users that lie in orthogonal subspaces can reduce the interference level and improve the spectral efficiency by enabling spreading code reuse.

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The contribution of this work is to show that the combination of subspace-aware user selection and the well-known MOE receiver algorithm reaches an effective data user separation, even when the users share the same spreading code. The following notations are used in the paper:  $\Re$ ,  $\Im$ ,  $\mathcal{R}$ ,  $\mathcal{C}$ ,  $(\cdot)^*$ ,  $(\cdot)^T$ ,  $(\cdot)^H$ ,  $\langle \cdot \rangle$ , and  $\|\cdot\|$ , denoting real part, imaginary part, real number, complex number, complex conjugate, transpose, hermitian, correlation, and norm, respectively. Scalars are written in lowercase, vectors in bold lowercase, and matrices with bold uppercase letters. The paper is organized as follows: the system model is presented in Section 2, and the adaptive blind receiver is analyzed in Section 3, followed by scheduling schemes presented in Section 4. Simulation results are presented in Section 5, followed by paper conclusions.

## 2 System model

The system model for the downlink of a wireless communication system is illustrated in Figure 1. The system consists of a single base station (BS) with two transmit (Tx) antennas  $j = 1, 2$  and  $K$  active user equipments (UEs) with single-element antennas.

In case of flat fading and rich scattering, the channel gain from a  $j$ th Tx antenna to a  $k$ th UE is described by a zero-mean circularly symmetric complex Gaussian random variable (RV),  $g_{jk}$ , for  $j = 1, 2$  and  $k = 1, \dots, K$ . For simplicity, we assume that all UEs are spatially homogeneously distributed and experience independent fading. We also assume that each UE has a low-rate, reliable, and delay-free feedback channel to the BS. For convenience, we will assume that the user of interest is  $k = 1$ . The signal received by user 1, in a single symbol interval  $[0, T]$ , can be written as

$$r_1(t) = \sum_{k=1}^K (\mathbf{g}_1^T \cdot \mathbf{w}_k) b_k s_k(t) + \sigma n_1(t), \quad (1)$$

where  $\mathbf{g}_1 = [g_{11} \ g_{21}]^T$  is the channel gain vector from the BS to the desired user with unit variance entries.  $\mathbf{w}_k = [w_{1k} \ w_{2k}]^T$  is the Tx channel weight vector that maximizes the received energy for the desired user.  $b_k \in$

$\{+1, -1\}$  represents the identical and independent distributed users data stream with zero mean and unit variance.  $s_k(t)$  is the unit energy spreading code of the  $k$ th user.  $n_1(t)$  is the additive white Gaussian noise (AWGN) component with unit variance, and  $\sigma$  is a scalar factor that affects the variance level of the AWGN component.

Let  $\{\psi_1(t), \dots, \psi_L(t)\}$  be a set of  $L$  orthonormal signals defined on  $i$ th  $[iT, iT + T]$  time interval. The received signal vector  $\mathbf{r}_1 \in \mathcal{C}^{L \times 1}$  of the desired user is the  $L$ -dimensional representation of  $r_1(t)$  on the basis  $\{\psi_1(t), \dots, \psi_L(t)\}$ , that is, the  $l$  component of the column vector  $\mathbf{r}_1$  is

$$r_{1l}[i] = \int_{iT}^{iT+T} r_1(t) \psi_l^*(t) dt \quad l = 1, \dots, L. \quad (2)$$

Furthermore, we define the components of the spreading code vector  $\mathbf{s}_k \in \mathcal{R}^{L \times 1}$  as

$$s_{kl}[i] = \int_{iT}^{iT+T} s_k(t) \psi_l^*(t) dt \quad l = 1, \dots, L \quad (3)$$

and the component of the  $L$ -dimensional Gaussian vector  $\mathbf{n}_1 \in \mathcal{C}^{L \times 1}$  as

$$n_{1l}[i] = \int_{iT}^{iT+T} n_1(t) \psi_l^*(t) dt \quad l = 1, \dots, L. \quad (4)$$

For convenience, the received signal (Equation 2) is expressed in vector form:

$$\mathbf{r}_1[i] = h_{11} b_1[i] \mathbf{s}_1 + \dots + h_{1K} b_K[i] \mathbf{s}_K + \sigma \mathbf{n}_1[i] \quad (5)$$

$$\mathbf{r}_1[i] = \mathbf{S} \mathbf{H} \mathbf{b}[i] + \sigma \mathbf{n}_1[i], \quad (6)$$

where

$$\mathbf{S} \stackrel{\text{def}}{=} [\mathbf{s}_1 \ \dots \ \mathbf{s}_K], \quad (7)$$

$$h_{11} \stackrel{\text{def}}{=} (\mathbf{g}_1^T \cdot \mathbf{w}_1), \quad (8)$$

$\vdots$

$$h_{1K} \stackrel{\text{def}}{=} (\mathbf{g}_1^T \cdot \mathbf{w}_K), \quad (9)$$

$$\mathbf{H} \stackrel{\text{def}}{=} \text{diag}(h_{11}, \dots, h_{1K}), \quad (10)$$

$$\mathbf{b}[i] \stackrel{\text{def}}{=} [b_1[i] \ \dots \ b_K[i]]^T. \quad (11)$$

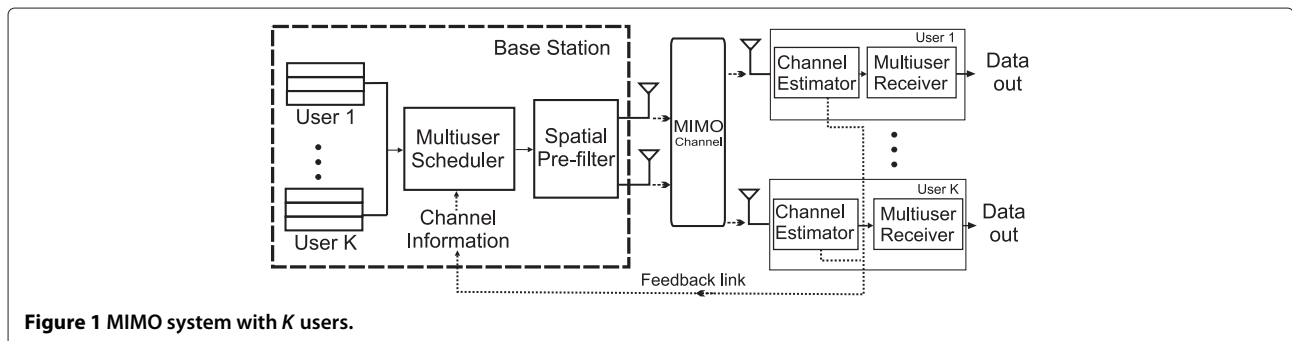


Figure 1 MIMO system with  $K$  users.

The autocorrelation matrix of the received signal  $\mathbf{r}_1[i]$  is given by

$$\mathbf{R}_{rr} = E[\mathbf{r}_1[i] \mathbf{r}_1^H[i]] = (\mathbf{S}\mathbf{H})(\mathbf{S}\mathbf{H})^H + \sigma^2 \mathbf{I}, \quad (12)$$

$$\mathbf{R}_{rr} = \mathbf{S}\mathbf{A}\mathbf{S}^H + \sigma^2 \mathbf{I}, \quad (13)$$

where  $\mathbf{A} = \mathbf{H}\mathbf{H}^H = \text{diag}(|h_{11}|^2, \dots, |h_{1K}|^2)$  with  $a_{kk} = |h_{1k}|^2$   $k = 1, \dots, K$ , and  $\mathbf{I}$  is the  $L \times L$  identity matrix. The system model adopted is illustrated in Figure 2.

### 3 Adaptive blind receiver

The adaptive MOE detector was first proposed by Honig et al. [15] and is blind to some extent because a training sequence is not required. It is therefore commonly known as the *adaptive blind receiver*. The adaptive MOE algorithm is implemented by a transversal filter which converges to the MMSE detector to within a scaling factor [11]. Figure 3 shows the implementation structure. A key property of every linear multiuser receiver is that the impulse response can be decomposed as a sum of two orthogonal components. One of those components is equal to the spreading code of the desired user which is assumed to be known and fixed throughout this section, that is,  $\mathbf{c}[i] = \mathbf{s}_1 + \mathbf{x}_1[i]$ , where  $\mathbf{x}_1^H \mathbf{s}_1 = 0$ . The cost function is the variance of the filter output, known as *output energy* (OE), and is minimized over the adaptive component  $\mathbf{x}_1[i]$  subject to the constraint  $\langle \mathbf{c}[i], \mathbf{s}_1 \rangle = 1$  [15]. The OE is given by [15]

$$\xi[i] = \|\mathbf{c}^H[i] \mathbf{r}_1[i]\|^2, \quad (14)$$

where  $i$  is the time index interval, and the MOE may be written as

$$\xi_{\min} = \min E \left[ \|\mathbf{c}[i]^H \mathbf{r}_1[i]\|^2 \right] \text{ s.t. } \langle \mathbf{c}[i], \mathbf{s}_1 \rangle = 1. \quad (15)$$

Taking into consideration that the receiver knows the actual weighted channel gain ( $h_{11}$ ), the decision on  $b_1$  is given by

$$\hat{b}_1 = \text{sgn}(\Re\{h_{11}^* \langle \mathbf{c}, \mathbf{r}_1 \rangle\}). \quad (16)$$

Applying the gradient descent algorithm to the cost function (Equation 14), the stochastic gradient adaptation rule is [15]

$$\mathbf{x}_1[i+1] = \mathbf{x}_1[i] - \mu \mathbf{z}^*[i] \mathbf{P}_{\mathbf{s}_1}^\perp \mathbf{r}_1[i], \quad (17)$$

where  $\mathbf{P}_{\mathbf{s}_1}^\perp = \mathbf{I} - \mathbf{s}_1 \mathbf{s}_1^H$  is the matrix that projects vectors, pre-multiplies it, onto the space orthogonal to  $\mathbf{s}_1$ , and  $\mu \in \mathcal{R}^{1 \times 1}$  is the step-size. In the work of [16], the authors show that the trajectory of the tap-weight vector,  $\mathbf{x}_1$ , depends on the eigenvalues of the equivalent autocorrelation matrix projected on a spreading code subspace orthogonal to the desired user. This subspace approach analysis shows also that the transient behavior of the MOE learning curve just depends on the largest  $K - 1$  eigenvalues of the equivalent matrix autocorrelation when the adaptive component is initialized in  $\mathbf{x}_1[0] = 0$  [17]. Based on this, when two users share the spreading code, they share the same eigenvalue too. Therefore, based only on the spreading code data separation, the tap adaptation algorithm cannot distinguish two users with the same spreading code. In the next section, the error probability analysis of this receiver is presented.

#### 3.1 Probability of error

To analyze the bit error rate of the blind adaptive receiver  $P_1^b(\sigma)$ , we can consider  $K$  users case. First, we treat the elements of the weighted channel matrix  $\mathbf{H}$  as a constant value (block-fading) to derive a first expression. Then, we find the expected value of the error probability in a semi-analytical way, over the marginal probability density function (PDF) of each element of  $\mathbf{H}$ .

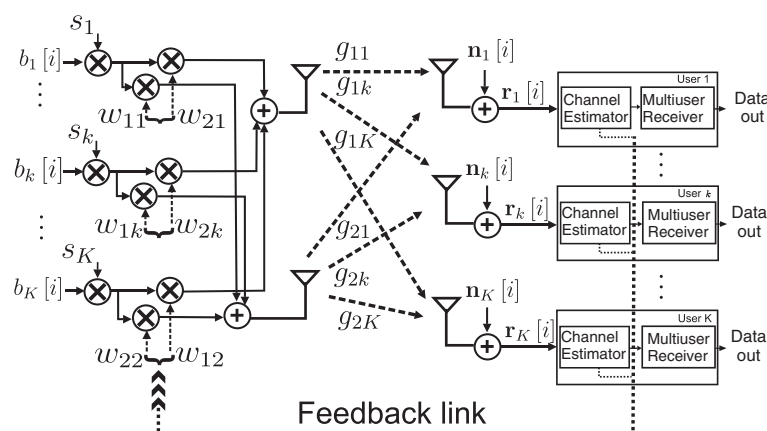
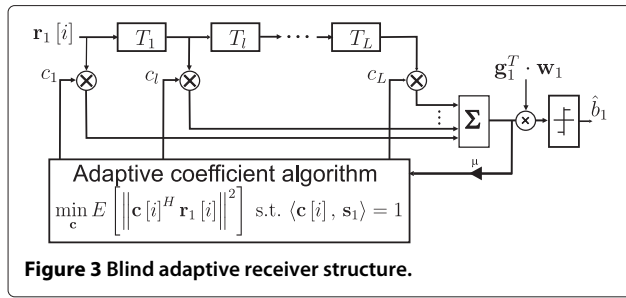


Figure 2 System model scheme.



**Figure 3** Blind adaptive receiver structure.

The probability of error is

$$\begin{aligned}
 P_1(\sigma) &= P[\hat{b}_1 \neq b_1] \\
 &= \sum_{b_1 \in \{1, -1\}} P[\hat{b}_1 \neq b_1 | b_1] P[b_1] \\
 &= \frac{1}{2} \sum_{b_1 \in \{1, -1\}} P[\hat{b}_1 \neq b_1 | b_1], \quad (18)
 \end{aligned}$$

with

$$P[\hat{b}_1 \neq b_1 | b_1] = \frac{1}{2^{K-1}} \sum_{j=1}^{2^{K-1}} P[\hat{b}_1 \neq b_1 | b_1, \epsilon_j], \quad (19)$$

where  $\epsilon_j \in \mathcal{R}^{(K-1) \times 1}$  belong to a set of  $2^{K-1}$  vectors that contains all the data combination of the interfering users. Focusing on one term of Equation 19 and taking into account that if  $b_1 = -1$  in Equation 16, the filter output is

$$h_{11}^* \langle \mathbf{r}_1, \mathbf{c} \rangle = -|h_{11}|^2 + q + \sigma \|\mathbf{c}\| h_{11}^* m_1, \quad (20)$$

where  $m_1$  is another zero-mean circularly symmetric complex Gaussian random variable, and

$$q = h_{11}^* \sum_{k=2}^K h_{1k} (\rho_k + \langle \mathbf{x}_1, \mathbf{s}_k \rangle) \epsilon_j(k-1), \quad (21)$$

represents the multiaccess interference (MAI). Considering Equation 20, one term of Equation 19 is given by

$$\frac{1}{2} P[-|h_{11}|^2 + \Re\{q\} < \Re\{\sigma h_{11}^* \|\mathbf{c}_1\| m_1\}]. \quad (22)$$

Proceeding in a similar way with the other terms of Equation 19 and replacing in Equation 18, we have  $P_1(\sigma)$  in Equation 26. Then we must take expectation value over the PDF of  $h_{11}$  and  $h_{1k}$  in order to get  $P_1^b(\sigma)$ . In Equation 26, the phase term  $\frac{h_{11}^*}{|h_{11}|}$  only affects the phase distribution of the random variable  $h_{1k}$  inside the  $Q(\cdot)$  function, whose statistic is uniform over  $[0, 2\pi]$  and thus can be dropped. The expression of  $P_1^b(\sigma)$  can be rewritten as in Equation 27 where the expectation value is taken over each  $h_{1k}$ .

## 4 Scheduling schemes

From Equation 27 we can observe that error probability is a function of two MAI terms. One of them depends directly on the weighted channel gain of the desired user, and the other is related to the blind adaptive algorithm whose performance is also influenced by the co-scheduled weighted channel gains. In this section, we present three different schedulers that try to reduce the MAI.

- *Scheduler A.* In order to minimize the interference level experienced by the receiver, the first idea is to schedule users with orthogonal weight channel vectors [9]. Based on this, the weighted channel gains of the scheduled users result uncorrelated, that is,

$$E[(\mathbf{g}_1^T \cdot \mathbf{w}_1)^* (\mathbf{g}_1^T \cdot \mathbf{w}_2)] = 0, \quad (23)$$

where only two users can be used because the number of transmit antennas defines the number of orthogonal users that can be served simultaneously. Equation 23 can be interpreted in a different way, noting that the two scheduled users' weight channel vectors should be collinear and opposite in phase at the receiver.

- *Scheduler B.* This scheduling strategy follows from the observation that the impact of interference on the performance of blind adaptive receiver is through the real term of the argument of  $Q(\cdot)$  function. Due to the fact that the blind adaptive algorithm decodes the desired user in a direction orthogonal to interference and noise, we can project some part of the interference in a subspace orthogonal to the desired data by selecting users with proper weight channel vectors that result in a  $\pi/2$  relative rotation. In the case of  $K = 2$ , the scheduler selects two users that report orthogonal weight channel vectors in the same fashion as Scheduler A, but instead of pre-filtering the transmit signal with those reported weights, one weight channel vector is rotated by  $\pi/2$  before using in the pre-filtering matrix. That is to say that if  $\mathbf{w}'_1$  and  $\mathbf{w}_2$  are the orthogonal weights reported by the scheduled users, then a rotation is applied to  $\mathbf{w}'_1$ , yielding

$$\mathbf{w}_1 = \mathbf{w}'_1 e^{j\pi/2}, \quad (24)$$

and then pre-filtering with  $\mathbf{w}_1$  and  $\mathbf{w}_2$  is used at BS. The condition imposed by Equation 24 does not change the correlation between them nor the purpose of energy maximization at the receiver side of each user. In the case of  $K \geq 2$  and an even number of users, the BS can schedule  $2N$  users

distributed in  $N$  groups of two users with orthogonal weight channel vectors, where  $N$  represents the available spreading code. The received signal in the time interval for the desired user can be written as

$$\mathbf{r}_1 = \sum_{i=1}^K \left[ (\mathbf{g}_1^T \cdot \mathbf{w}_{2k-1}) b_{2k-1} + (\mathbf{g}_1^T \cdot \mathbf{w}_{2k}) b_{2k} \right] \mathbf{s}_k + \sigma \mathbf{n}_1, \quad (25)$$

with  $\mathbf{w}_{2k}^H \mathbf{w}_{2k-1} = 0$ . With the signal processing at the receiver in mind, the condition imposed by Equation 24 minimizes the interference caused by user 2 because its real component is almost cancelled.

$$P_1(\sigma) = \frac{1}{2^K} \sum_{j=1}^{2^{K-1}} \left[ Q \left( \frac{|h_{11}|}{\sqrt{\frac{\sigma^2}{2} (1 + \|\mathbf{x}_1\|^2)}} - \frac{\Re \left\{ \frac{h_{11}^*}{|h_{11}|} q \right\}}{\sqrt{\frac{\sigma^2}{2} (1 + \|\mathbf{x}_1\|^2)}} \right) + Q \left( \frac{-|h_{11}|}{\sqrt{\frac{\sigma^2}{2} (1 + \|\mathbf{x}_1\|^2)}} + \frac{\Re \left\{ \frac{h_{11}^*}{|h_{11}|} q \right\}}{\sqrt{\frac{\sigma^2}{2} (1 + \|\mathbf{x}_1\|^2)}} \right) \right] \quad (26)$$

$$P_1^b(\sigma) = \frac{1}{2^{K-1}} \sum_{j=1}^{2^{K-1}} E \left[ Q \left( \frac{|h_{11}| + \Re \left\{ \sum_{k=2}^K \frac{h_{11}^* h_{1k}}{|h_{11}|} (\rho_k + \langle \mathbf{x}_1, \mathbf{s}_k \rangle) \epsilon_j(k-1) \right\}}{\sqrt{\frac{\sigma^2}{2} (1 + \|\mathbf{x}_1\|^2)}} \right) \right]. \quad (27)$$

- *Scheduler C.* This scheduling strategy is based on the observation already done for Scheduler B, but in this case, the scheduler selects the users that report the same weight channel vector, then only a rotation is applied to one of them in order to minimize the interference. For the case of  $K = 2$ , that is, if  $\mathbf{w}'_1$  and  $\mathbf{w}_2$  are the weights reported by the scheduled users and  $\mathbf{w}'_1 = \mathbf{w}_2$ , then a rotation is applied to  $\mathbf{w}_2$ , yielding
- *Scenario 1 (Sc-1).* Only one group with two users using different spreading codes is active.
- *Scenario 2 (Sc-2).* Six groups with two users using the same spreading codes are active.
- *Scenario 3 (Sc-3).* Similar to Sc-2 except in one group, the one whose performance is analyzed. In this group of interest, the users do not share the same spreading code.

$$\mathbf{w}_2 = \mathbf{w}_2 e^{j\pi/2}. \quad (28)$$

Note that the signal processing at the BS with Schedulers B and C only consists of a relative rotation of the two scheduled users. In this way, these schedulers are projecting the interference data onto a subspace orthogonal to the desired data. For an even number of users, i.e.,  $K = 2N$ , the BS can schedule these  $K$  users in  $N$  groups of two users using  $N$  different spreading codes and selecting the users in each group based on their reported weight channel vectors.

## 5 Simulation results

In this section, we investigate the system performance under scheduling schemes (23), (24), and (28) using two types of detection: match filtering and adaptive blind interference cancellation. A Gold sequence of length 7 and phase quantized weight channel vectors for high-speed downlink packet access (HSDPA) mode 1 compatibility were selected for the simulation [18]. According to this, three scenarios are considered:

Figure 4 shows that spreading code reuse leads to a full performance degradation for both detection schemes when Scheduler A (Equation 23) is used. This behavior can be explained taking into account that both interference and desired signals are collinear with this scheduling strategy. In this case, the use of different spreading codes is essential to recover performance degradation, as shown in the curves as solid lines. For comparison, the two-user scenario is plotted in the figure in order to evaluate the performance degradation with higher multi-user interference. Figure 5 shows the performance of the ABR and match filter receiver (MF) with Scheduler B, i.e., the one that uses  $\pi/2$  rotation, in the same three scenarios. This scheduler enables code reuse since the performance of ABR is slightly degraded when the same spreading code is used in the group (ABR performance in Sc-3 degrades less than 1 dB compared with that in Sc-2). This ABR behavior is due to the fact that Scheduler B adjusts the data of the scheduled users to arrive with  $\pi/2$  rotation, so the ABR algorithm can work properly. On the other hand, Scheduler A forces data user 1

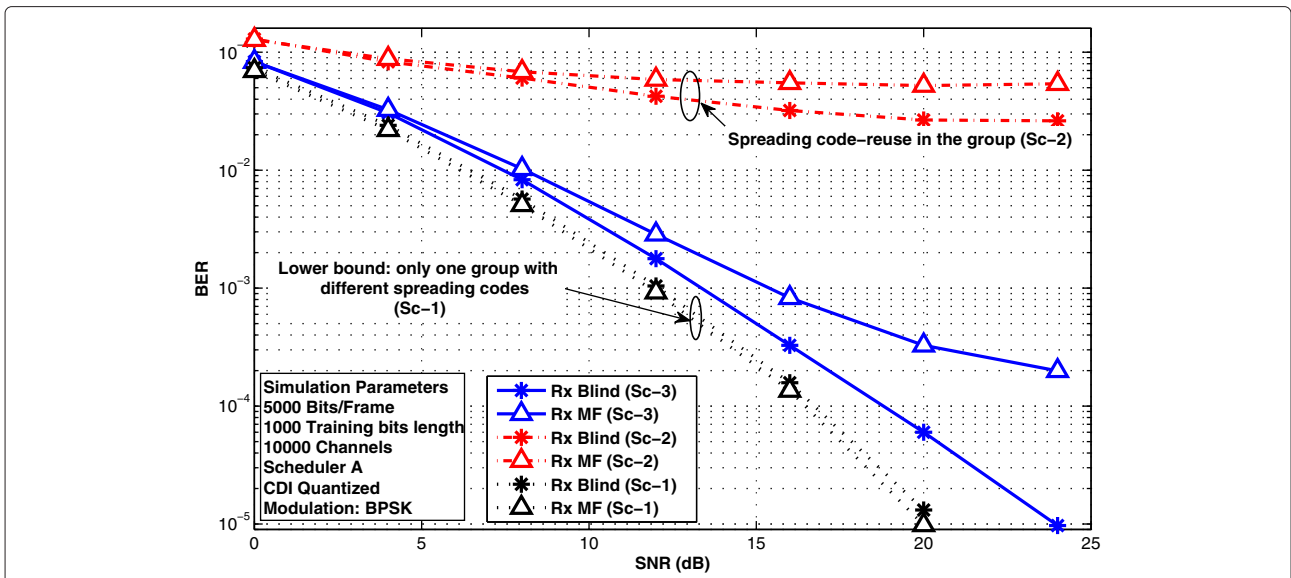


Figure 4 Blind adaptive receiver performance with Scheduler A.

and user 2 to be collinear and with opposite phase at the receiver, so the ABR algorithm cannot separate the users. In Sc-2 also, the performance of MF improves with Scheduler B. On the other hand, the use of Scheduler B in Sc-3 only slightly helps improve the performance. Figure 6 shows the performance of ABR and MF with Scheduler C. First of all, note that MF performance is almost the same with Sc-2 and Sc-3; therefore, code reuse does not degrade the MF performance when Scheduler C is used.

Using an ABR in SC-3, a performance improvement of almost 5 dB with respect to MF is achieved with this scheduler. It is interesting to note that Scheduler C improves the ABR in Sc-2. This is because the users scheduled in each group are the ones that reported the same weight channel vectors, and therefore, applying a  $\pi/2$  rotation to one of them, the component of the intra-group interference, orthogonal to the desired signal, is maximized at the receiver. Figure 7 shows the comparative performance of the

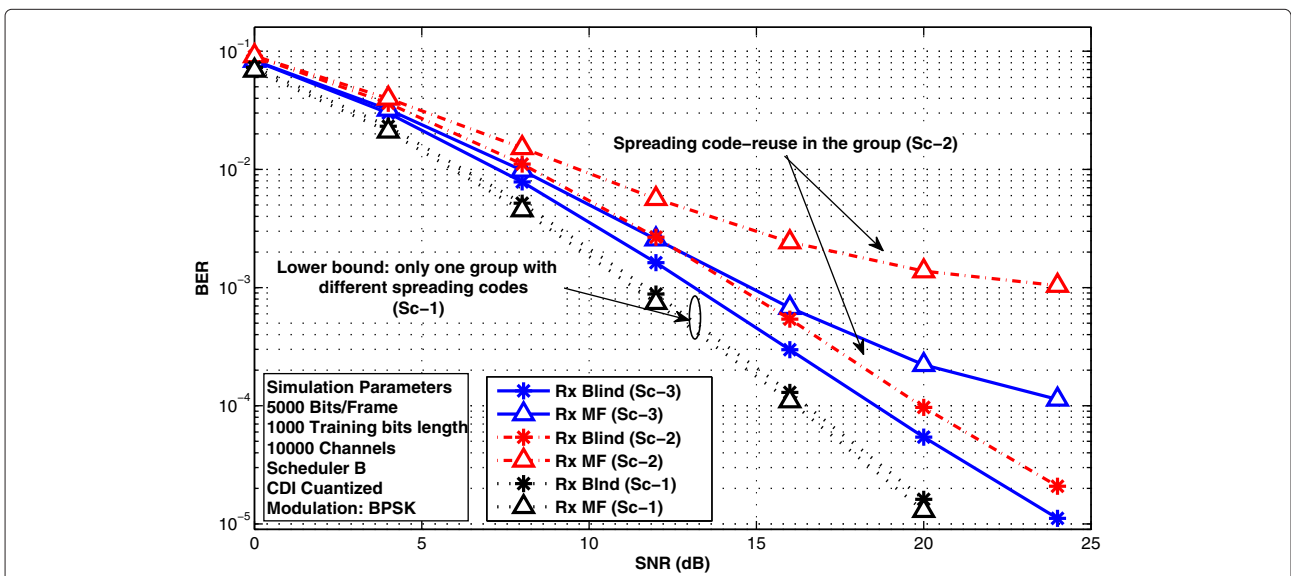


Figure 5 Blind adaptive receiver performance with Scheduler B.

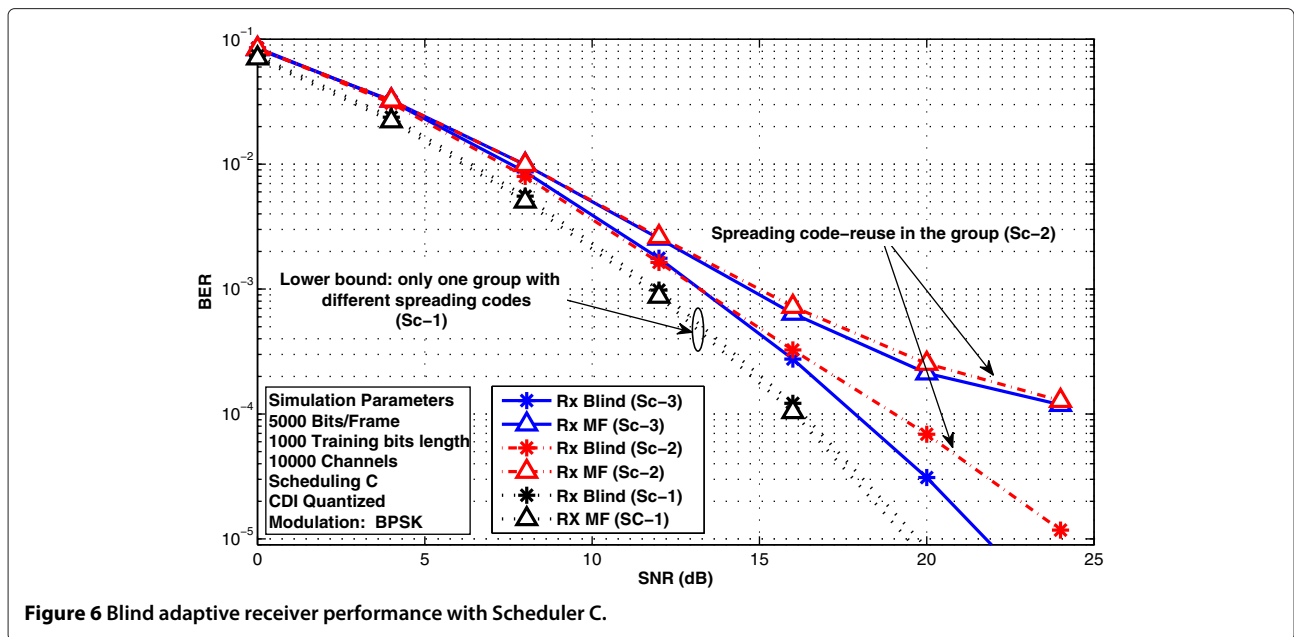


Figure 6 Blind adaptive receiver performance with Scheduler C.

ABR with the three types of schedulers in Sc-2. The performance achieved by Scheduler C with respect to Scheduler B is due to the fact that interference signal lie on subspaces orthogonal to the desired signal, and in this situation, a perfect data separation can be performed by ABR.

### 6 Conclusions

We have studied the performance of the adaptive blind MOE receiver in a  $2 \times 1$  MIMO scenario with practical UE schemes to take advantage of multiuser diversity

in a multiple-antenna broadcasting channel with limited feedback. New scheduling schemes that try to reduce interference projecting the non-canceled interference in a subspace orthogonal to the desired signal at the receiver is proposed in this paper for closed-loop MIMO system. The combination of the proposed schedulers and adaptive blind detection enables code reuse, making it possible to achieve higher spectrum efficiency with low complexity receivers. The proposed schedulers were analyzed for the practical case wherein the amount of feedback channel is compatible with mode 1 of the HSDPA technology.

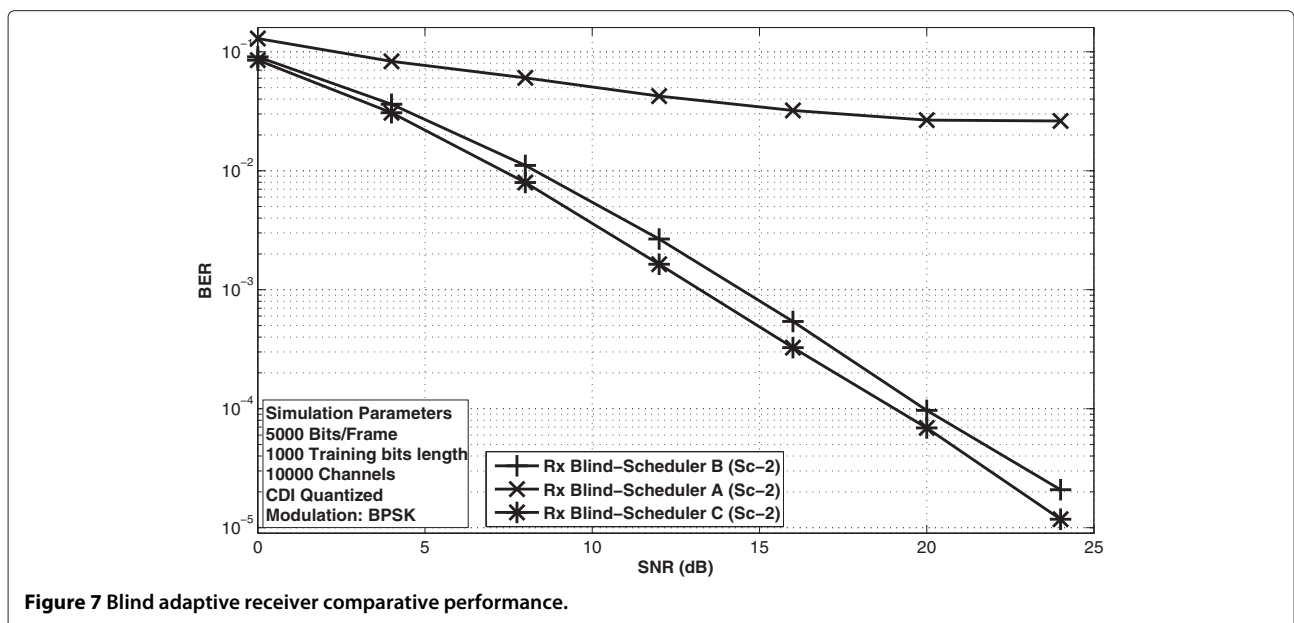


Figure 7 Blind adaptive receiver comparative performance.

#### Competing interests

Both authors declare that they have no competing interests.

#### Acknowledgements

This study was supported by The National Scientific and Technical Research Council (CONICET) under grant no. 1917/12, ANPCyT under grant PICT2011-2527, and SeCyT-UNC.

Received: 31 December 2012 Accepted: 30 April 2013

Published: 24 May 2013

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Cite this article as: Mendoza and Corral-Briones: Scheduling schemes with adaptive blind detection for code reuse in multiuser MIMO systems. *EURASIP Journal on Advances in Signal Processing* 2013 **2013**:109.

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