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LINEAR RECEIVER INTERFACES FOR MULTIUSER MIMO COMMUNICATIONS

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ABSTRACT

We consider the uplink of a DS-CDMA wireless communication system with multiple users equipped with several transmit antennas.

We assume that a multiple-antenna subsystem is added to an existing multiuser detector and we compare the performance of this receiver and that of an optimum receiver accounting for both spatial and multiple-access interference simultaneously. In the former case we say that the receiver is separate whereas in the latter we say that the receiver is joint.

Several classes of separate and joint linear receivers are considered and their performance is evaluated asymptotically and by simulation.

1. INTRODUCTION

Many research studies have been carried out in the last two decades focusing on multiuser detection [5] and several existing receivers exploit this technique to enhance user separation over a multiple-access channel. Several receiver architectures are based on code division multiple access (CDMA), which is also being discussed for 4G standards (see, e.g., [9]).

The development of multiple-input multiple-output (MIMO) communication technologies, with their promise of dramatically increasing the system capacity [3,10,15], has to cope with the existence of multiuser detection-based systems which are not designed for MIMO processing.

Only recently, multiuser detection has been considered for MIMO communications but these methods are supposed to play an important role in the development of 4G wireless mobile systems. Many studies have been published on the subject. Focusing on the uplink, Hjørungnes [7] derives the optimum linear FIR MMSE receivers with perfect CSIT and CSIR. Horlin and Vandendorpe [6] propose a centralized precoding algorithm for DS-CDMA based on signal-to-interference plus noise (SINR) optimization. Another optimum precoding algorithm based on MMSE is derived by Serbetli and Yener [12]. Shahbazpanahi *et al.* derive in [13] a minimum variance linear receivers based on space–time block codes. Shen and Burr [14] study a receiver scheme based on space–time turbo codes. Mantravadi *et al.* [11] consider wideband CDMA and study the performance of linear receivers with random spreading sequences using large-system analyses. Their system model is similar to the one we consider here.

Since multiuser MIMO communication systems are affected by high system complexity, we propose a modular approach based on the separation of the spatial interference and multiple-access interference (MAI) mitigation tasks, both implemented by linear receivers. Then, we regard the MIMO subsystem as an *add-on feature* to existing multiuser receivers, aimed to achieve most of the available performance gain. Accordingly, we obtain receiver schemes that are referred to as *separate receivers*.

Oppositely, when the receiver design takes into account all sources of interference affecting the received signal, we obtain receiver schemes that are referred to as *joint receivers*.

In this work we present performance results relevant to several standard and optimized linear receivers (in a sense to be clarified later) described in terms of asymptotic power gain (analytic) and frame error rate (FER). Analytic results are based on large-system analyses applied to the linear receivers considered.

2. MULTIUSER MIMO MULTIPLE-ACCESS CHANNEL

We consider the uplink of a multiuser multiple-access MIMO system adopting CDMA as its multiple-access scheme, with K users transmitting to one receiver. We assume that the kth user (for $k = 1,\dots,K$) is equipped with t_k transmit antennas, so that the total number of transmit antennas is $t \triangleq \sum_k t_k$. The receiver is equipped with r antennas. Direct sequence spread spectrum is used. Different transmit antennas are assigned different spreading sequences having the same length S (spreading factor). The spreading sequence transmitted by the kth user from the ith antenna ($k = 1,\dots,K$ and $i = 1,\dots,t_k$) is denoted by the row-vector

$$\mathbf{s}_{k,i} = (s_{k,i1},\dots,s_{k,iS}) \in \mathbb{C}^S.$$

We assume the normalization condition $\|\mathbf{s}_{k,i}\| = 1$.

The kth user transmits a symbol $x_{k,i}$ from the ith antenna by using the transmitted signal $x_{k,i}\mathbf{s}_{k,i}$. Transmitted symbols have zero mean and variance $E_s = \mathbb{E}[|x_{k,i}|^2]$. Channel gains relevant to the kth user are collected in the $r \times t_k$ random matrix $\mathbf{H}_k$, whose complex entries are assumed to be i.i.d. zero-mean circularly symmetric complex Gaussian random variables with variance $1/r$ (their distribution is denoted by $\mathscr{N}_c(0,1/r)$). The additive noise at the receiver is given by an $r \times S$ random matrix $\mathbf{Z}$ with i.i.d. entries distributed as $\mathscr{N}_c(0,N_0)$. The channel can be described in two equivalent ways:

- *Separate channel model.* In this case, the received signal corresponding to one symbol interval is given by the $r \times S$ matrix:

$$\mathbf{Y} = \sum_{k=1}^{K} \mathbf{H}_k\mathbf{X}_k\mathbf{S}_k + \mathbf{Z} = \mathbf{H}\mathbf{X}\mathbf{S} + \mathbf{Z}\ . \tag{1}$$

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where

$$\begin{aligned} \mathbf{H} &= (\mathbf{H}_1,\dots,\mathbf{H}_K), \\ \mathbf{X}_k &= \mathrm{diag}(x_{k,i})_{i=1}^{t_k}, \\ \mathbf{X} &= \mathrm{diag}(\mathbf{X}_1,\dots,\mathbf{X}_K), \\ \mathbf{S}_k &= (\mathbf{s}_{k,1}^T,\dots,\mathbf{s}_{k,t_k}^T)^T, \\ \mathbf{S} &= (\mathbf{S}_1^T,\dots,\mathbf{S}_K^T)^T. \end{aligned}$$ [1]

- *Joint channel model.* The received signal corresponding to one symbol interval is given by the rS-column vector:

$$\mathbf{y} = \widetilde{\mathbf{H}}\mathbf{x} + \mathbf{z}, \qquad (2)$$

where

$$\begin{aligned} \mathbf{x} &\triangleq \mathrm{vec}(\mathbf{X}), \\ \mathbf{y} &\triangleq \mathrm{vec}(\mathbf{Y}), \\ \mathbf{z} &\triangleq \mathrm{vec}(\mathbf{Z}), \\ \widetilde{H}_{j+(\ell-1)r,i} &= H_{j,i}s_{i,\ell} \end{aligned}$$

for $j = 1,\dots,r$, $\ell = 1,\dots,S$, and $i = 1,\dots,t$. [2]

The design of the separate receiver we consider in this work is based on the structure of eq. (1). This channel equation separates the effects of spatial and multiple-access interference, which are accounted for by the matrices $\mathbf{H}$ and $\mathbf{S}$, respectively. On the opposite, eq. (2) merges the multiuser and MIMO features into the single matrix $\widetilde{\mathbf{H}}$ and hints the design of a *joint receiver*.

3. LINEAR JOINT RECEIVERS

Linear joint receivers are derived by referring to the channel equation (2). After linear processing of the received signal vector $\mathbf{y}$, the receiver output is given by

$$\widehat{x}_{k,i} = \arg\min_{x\in\mathscr{X}} |(\mathbf{F}_{\text{joint}}\mathbf{y})_{(k,i)} - x|^2,$$

where the matrix $\mathbf{F}_{\text{joint}}$ is defined according to one of the *standard* linear receiver interfaces listed as follows:

i) matched filter (MF);
ii) zero-forcing or decorrelator (ZF);
iii) linear minimum mean-square error (LMMSE).

Then, $\mathbf{F}_{\text{joint}}$ is given by:

$$\mathbf{F}_{\text{joint}} = \begin{cases} \widetilde{\mathbf{H}}^\dagger & \text{(MF)} \\ (\widetilde{\mathbf{H}}^\dagger\widetilde{\mathbf{H}})^{-1}\widetilde{\mathbf{H}}^\dagger & \text{(ZF)} \\ (\widetilde{\mathbf{H}}^\dagger\widetilde{\mathbf{H}} + \delta_s\mathbf{I}_t)^{-1}\widetilde{\mathbf{H}}^\dagger & \text{(LMMSE)} \end{cases} . \qquad (3)$$

4. SEPARATE LINEAR RECEIVERS

A general form of a separate linear receiver consists in processing the received signal matrix $\mathbf{Y}$ by pre- and post-multiplying it by two suitable matrices $\mathbf{A}$ and $\mathbf{B}$ and extracting the main diagonal of the result. We obtain the following column vector:

$$\widetilde{\mathbf{y}} = \mathrm{diag}(\mathbf{A}^\dagger\mathbf{Y}\mathbf{B}).$$ [3]

$\mathbf{A}$ and $\mathbf{B}$ are $r \times t$ and $S \times t$ matrices implementing the spatial interference and MAI mitigation, respectively.

Therefore, we select the matrices $\mathbf{A}$ and $\mathbf{B}$ according to one of the following *standard* ways:

$$\mathbf{A} = \begin{cases} \mathbf{H}^\dagger & \text{(MF)} \\ (\mathbf{H}^\dagger\mathbf{H})^{-1}\mathbf{H}^\dagger & \text{(ZF)} \\ (\mathbf{H}^\dagger\mathbf{H} + \delta_s\mathbf{I}_t)^{-1}\mathbf{H}^\dagger & \text{(LMMSE)} \end{cases} \qquad (4)$$

and

$$\mathbf{B} = \begin{cases} \mathbf{S}^\dagger & \text{(MF)} \\ \mathbf{S}^\dagger(\mathbf{S}\mathbf{S}^\dagger)^{-1} & \text{(DECOR)} \\ \mathbf{S}^\dagger(\mathbf{S}\mathbf{S}^\dagger + \delta_s\mathbf{I}_t)^{-1} & \text{(LMMSE)} \end{cases} . \qquad (5)$$

Every resulting linear receiver is named after the names of the matrices $\mathbf{A}$ and $\mathbf{B}$ which is based on. For example, if $\mathbf{A} = \mathbf{H}^\dagger$ and $\mathbf{B} = \mathbf{S}^\dagger(\mathbf{S}\mathbf{S}^\dagger + \delta_s\mathbf{I}_t)^{-1}$, the resulting linear receiver will be referred to as "MF-LMMSE receiver."

4.1 Optimum separate receivers

In addition to the standard linear receivers described above, we consider another linear receiver obtained by determining the optimum matrix $\mathbf{A}$ corresponding to one of the previously listed *standard* matrices $\mathbf{B}$. This optimization method, to be described in the following, leads to what we refer to as optimum separate receiver. Optimum separate receivers will be denoted as OPT-$\star$, where $\star$ is one of MF, DECOR, or LMMSE.

In order to derive the optimum matrix $\mathbf{A}$ for a given $\mathbf{B}$ we proceed as follows. For a fixed multiuser interface, characterized by the matrix $\mathbf{B}$, we look for the matrix $\mathbf{A}$ minimizing the MSE

$$\begin{aligned} J(\mathbf{A},\mathbf{B}) &\triangleq E_s^{-1}\mathbb{E}\left[|\widetilde{\mathbf{y}} - \mathbf{x}|^2\right] \\ &= E_s^{-1}\mathbb{E}\left[\left|\mathrm{diag}(\mathbf{A}^\dagger\mathbf{H}\mathbf{X}\mathbf{S}\mathbf{B}) - \mathbf{x} + \mathrm{diag}(\mathbf{A}^\dagger\mathbf{Z}\mathbf{B})\right|^2\right] \\ &= \sum_{i=1}^{t}\Big\{\mathbf{a}_i^\dagger\mathbf{H}\mathrm{diag}(\mathbf{S}\mathbf{b}_i\mathbf{b}_i^\dagger\mathbf{S}^\dagger)\mathbf{H}^\dagger\mathbf{a}_i + 1 + \delta_s|\mathbf{a}_i|^2|\mathbf{b}_i|^2 \\ &\quad -2\,\mathrm{Re}[\mathbf{a}_i^\dagger\mathbf{h}_i\mathbf{s}_i\mathbf{b}_i]\Big\}, \end{aligned} \qquad (6)$$

where $\delta_s = N_0/E_s$ and $\mathbf{a}_i$, $\mathbf{b}_i$, and $\mathbf{h}_i$ denote the ith columns of $\mathbf{A}$, $\mathbf{B}$, and $\mathbf{H}$, respectively.

Notice that $J(\mathbf{A},\mathbf{B})$ is a convex function of the entries of $\mathbf{A}$ and $\mathbf{B}$. Therefore, it has a unique global minimum [2].

In the following we propose a double minimization method which is guaranteed to reach the minimum since the resulting sequence of $J(\mathbf{A},\mathbf{B})$ values is real, monotonically decreasing, and lower bounded by zero, and hence it has a limit point.

We can see that the columns of $\mathbf{A}$, minimizing the MSE for the given $\mathbf{B}$, are given by the following r-column vectors:

$$\mathbf{a}_i = \left(\mathbf{H}\mathrm{diag}(\mathbf{S}\mathbf{b}_i\mathbf{b}_i^\dagger\mathbf{S}^\dagger)\mathbf{H}^\dagger + \delta_s|\mathbf{b}_i|^2\mathbf{I}_r\right)^{-1}\mathbf{h}_i\mathbf{s}_i\mathbf{b}_i. \qquad (7)$$

In the following, eq. (7) is used to obtain an explicit expression of the optimum $\mathbf{A}$, corresponding to the three multiuser interfaces considered. For convenience, we define the

[2] $\mathrm{vec}(\mathbf{A})$ denotes the column vector obtained by stacking the columns of $\mathbf{A}$ on top of each other.

[3] Notation $(\cdot)^\dagger$ denotes Hermitian conjugation.

following matrices:

$$\begin{aligned}\mathbf{W} &\triangleq \mathbf{H}^\dagger\mathbf{H}(t\times t \text{ matrix}),\\ \mathbf{Q} &\triangleq \mathbf{S}\mathbf{S}^\dagger(t\times t \text{ matrix}),\\ &= (\mathbf{q}_1,\ldots,\mathbf{q}_t)\\ \mathbf{D} &\triangleq (\mathbf{Q}+\delta_s\mathbf{I}_t)^{-1}(t\times t \text{ matrix}).\end{aligned}$$

- **OPT-MF**: we have $\mathbf{B}=\mathbf{S}^\dagger$ and thus

$$\mathbf{a}_i=\left(\mathbf{H}\widetilde{\mathbf{Q}}_i\mathbf{H}^\dagger+\delta_s\mathbf{I}_r\right)^{-1}\mathbf{h}_i \quad (8)$$

  where $\widetilde{\mathbf{Q}}_i$ is a diagonal matrix, $(\widetilde{\mathbf{Q}}_i)_{m,m}=|q_{m,i}|^2$ for $m=1,\ldots,t$, and $q_{m,i}$ is the m,ith entry of $\mathbf{Q}$.
- **OPT-DECOR**: we have $\mathbf{B}=\mathbf{S}^\dagger\mathbf{Q}^{-1}$ and thus

$$\mathbf{a}_i=(\mathbf{h}_i\mathbf{h}_i^\dagger+\delta_s p_i\mathbf{I}_r)^{-1}\mathbf{h}_i=\mathbf{h}_i(|\mathbf{h}_i|^2+\delta_s p_i)^{-1}$$

  where we set $p_i\triangleq(\mathbf{Q}^{-1})_{i,i}$. Then $\mathbf{A}$ is given by

$$\mathbf{A}=\mathbf{H}\left(\mathrm{diag}(\mathbf{W}+\delta_s\mathbf{Q}^{-1})\right)^{-1}. \quad (9)$$

  Notice that the right multiplication of $\mathbf{H}$ by a diagonal matrix does not affect the decision rule for constant-energy modulations. Thus, in these cases, the OPT-DECOR receiver is equivalent to MF-DECOR.
- **OPT-LMMSE**: we have $\mathbf{B}=\mathbf{S}^\dagger(\mathbf{Q}+\delta_s\mathbf{I}_t)^{-1}=\mathbf{S}^\dagger\mathbf{D}$ and $\mathbf{b}_i=\mathbf{S}^\dagger\mathbf{d}_i$ where $\mathbf{d}_i$ is the ith column of $\mathbf{D}$. Hence,

$$\mathbf{a}_i=\left(\mathbf{H}\mathrm{diag}(\mathbf{Q}\mathbf{d}_i\mathbf{d}_i^\dagger\mathbf{Q}^\dagger)\mathbf{H}^\dagger+\delta_s\mathbf{d}_i^\dagger\mathbf{Q}\mathbf{d}_i\mathbf{I}_r\right)^{-1}\mathbf{h}_i\mathbf{q}_i^\dagger\mathbf{d}_i\,. \quad (10)$$

An alternative separate receiver scheme is obtained by setting $\mathbf{A}=(\mathbf{H}\mathbf{H}^\dagger+\delta_s\mathbf{I}_r)^{-1}\mathbf{H}$ [1], which corresponds to a MIMO interface designed independently of the multiuser interface according to an MMSE criterion. We refer to the resulting receiver as LMMSE-$\star$ where $\star$ is one of MF, DECOR, or LMMSE.

5. JOINTLY OPTIMUM SEPARATE RECEIVER

In the previous section we assumed that mitigation of the spatial interference was accomplished by minimizing the MSE $J(\mathbf{A},\mathbf{B})$ over matrix $\mathbf{A}$ and for a fixed $\mathbf{B}$. In a similar way, we can fix $\mathbf{A}$ and find the optimum $\mathbf{B}$. The column of $\mathbf{B}$ are given by the following S-column vectors:

$$\mathbf{b}_i=\left(\mathbf{S}^\dagger\mathrm{diag}(\mathbf{H}^\dagger\mathbf{a}_i\mathbf{a}_i^\dagger\mathbf{H})\mathbf{S}+\delta_s|\mathbf{a}_i|^2\mathbf{I}_S\right)^{-1}\mathbf{s}_i^\dagger\mathbf{h}_i^\dagger\mathbf{a}_i\,. \quad (11)$$

Clearly, the optimum approach is to jointly minimize the MSE $J(\mathbf{A},\mathbf{B})$ with respect to both matrices $\mathbf{A}$ and $\mathbf{B}$. This leads to what we call *jointly optimum separate receiver*.

Opposite to our previous findings, the jointly optimum matrices seem not to be amenable to closed form. However, the following iterative algorithm leads to the solution of the optimization problem.

Let us write eq. (7) and eq. (11) as $\mathbf{a}_i=\boldsymbol{\phi}_1(\mathbf{b}_i)$ and $\mathbf{b}_i=\boldsymbol{\phi}_2(\mathbf{a}_i)$, respectively, as a shorthand notation. Then, the iterative algorithm can be described as follows:

1. Set $\mathbf{a}_i^{(0)}=\mathbf{0}$ and $\mathbf{b}_i^{(0)}=\mathbf{s}_i^\dagger$.
2. Then, for $n=0,1,2,\ldots,$
3. evaluate $\mathbf{a}_i^{(n+1)}=\boldsymbol{\phi}_1(\mathbf{b}_i^{(n)})$;
4. evaluate $\mathbf{b}_i^{(n+1)}=\boldsymbol{\phi}_2(\mathbf{a}_i^{(n+1)})$.
5. Stop when $|\mathbf{a}_i^{(n+1)}-\mathbf{a}_i^{(n)}|^2<\varepsilon$ and $|\mathbf{b}_i^{(n+1)}-\mathbf{b}_i^{(n)}|^2<\varepsilon$ for a given $\varepsilon>0$.

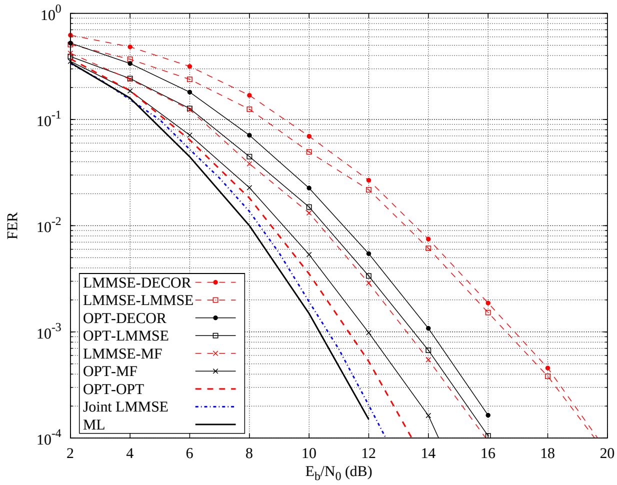

Figure 1: Performance of separate receivers for $K=2$, $t=4$, $r=8$, and $S=8$

Even though the jointly optimum separate receiver achieves better performance than the optimum separate receiver, its use is impractical. In fact, a joint LMMSE receiver achieves better error performance and it is simpler. However, we use it here as a benchmark to compare the performance of the optimum separate receivers.

6. RECEIVER COMPLEXITY

The complexity of the receiver schemes arises from two different sources:

1. The complexity entailed by the computation of the linear filter matrices ($\mathbf{A}$ and $\mathbf{B}$ for the separate and $\mathbf{F}_{\text{joint}}$ for the joint receiver).
2. The complexity entailed by the computation of the detection metrics ($\tilde{\mathbf{y}}$ for the separate and $\mathbf{F}_{\text{joint}}\mathbf{y}$ for the joint receiver).

The former depends on the linear receiver considered and we denote it by $\mathscr{C}_m$ complex arithmetic operations. The latter, assuming the linear filter matrices given, corresponds to $\mathscr{C}_d=2trS$ complex arithmetic operations per symbol interval. If we assume that the channel matrix and the spreading sequences remain constant for N symbol intervals, then the average complexity per symbol interval is

$$\mathscr{C}_a=\frac{1}{N}\mathscr{C}_m+\mathscr{C}_d\,. \quad (12)$$

Separate receivers have smaller filter complexity $\mathscr{C}_m$ than joint receivers because of the smaller sizes of the matrices involved. However, this complexity is reduced by the factor N so that the real advantage of separate receivers depends closely on the channel dynamics.

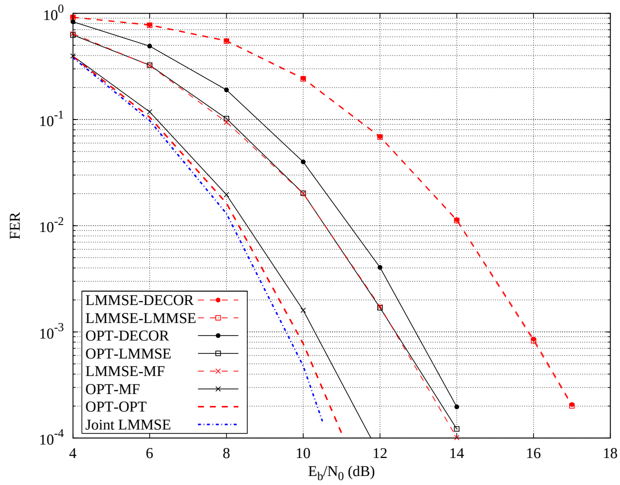

Figure 2: Performance of separate receivers for $K = 4$, $t = 16$, $r = 32$, and $S = 32$

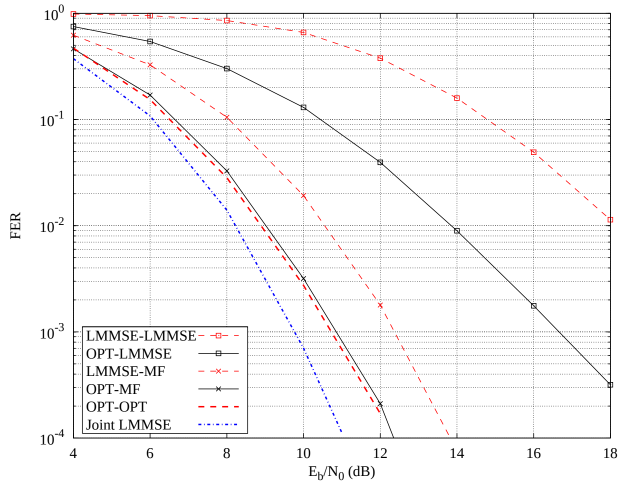

Figure 3: Performance of separate receivers for $K = 4$, $t = 16$, $r = 32$, and $S = 12$

7. SIMULATION RESULTS

We compare the receivers proposed in terms of frame error rate (FER) versus E_b/N_0. Every frame corresponds to one signalling interval and we assume QPSK modulation. Thus, each frame contains $2t$ bits. A frame error is defined as the occurrence of at least one symbol error for any user. Fig. 1 refers to a multiuser multiple-access MIMO system with $K = 2$ users, $t_k = 2$ antennas per user, $r = 8$ receive antennas, spreading factor $S = 8$. Spreading sequences are randomly generated with i.i.d. QPSK symbols. The figure reports the simulated FER of the OPT-$\star$ and LMMSE-MF. We also report the performance of the LMMSE-DECOR and LMMSE-LMMSE receivers described in [1]. Additionally, the figure includes the FERs corresponding to the (joint) ML, joint LMMSE (derived from channel equation (2)), and optimum separate receiver (labelled ML, Joint LMMSE, and OPT-$\star$, respectively). The joint receivers are discussed in detail in [1]. The ML receiver corresponds to the ML detection rule $\arg\min_{\mathbf{x}} \|\mathbf{y} - \widetilde{\mathbf{H}}\mathbf{x}\|^2$ (using the notation in (2)).

The FERs of the ML and Joint LMMSE receivers are very close to each other (about 0.3 dB apart). At FER$= 10^{-3}$, the optimum separate receiver performance is about 1 dB worse than the ML receiver. Among the other separate receivers, the best performance is achieved by the OPT-MF, which loses about 2 dB from the ML receiver at FER$= 10^{-3}$ and about 0.7 dB from the optimum separate receiver. The remaining separate receivers undergo more substantial performance degradations up to about 4 dB (OPT-LMMSE separate receiver). The figure shows also that the OPT-$\star$ receivers improve the performance of the corresponding LMMSE-$\star$ receivers by up to 3 dB.

Similar results are reported in Fig. 2 for a system with $K = 4$ users, $t_k = 4$ antennas per user, $r = 32$ receive antennas, and spreading factor $S = 32$ (the simulated ML performance is not shown in this case due to the huge computational load required). In this case the loss of the OPT-MF receiver with respect to the joint LMMSE (whose performance is expected to be close to the joint ML) is limited to about 0.6 dB at FER$= 10^{-3}$.

Comparing the performances of the OPT-LMMSE and OPT-MF receivers, it can be noticed that the former is worse than the latter, contrary to the common expectation that LMMSE outperforms MF. We think that this is due to the fact that the inverse matrix postmultiplication made in the OPT-LMMSE receiver disrupts the user separation more than it helps for noise reduction so that it is better to avoid it.

Fig. 3 reports the FER performance in the case of $K = 4$ users, $t_k = 4$ antennas per user, $r = 32$ receive antennas, and spreading factor $S = 12$. Since $S < t$ in this case, the LMMSE-DECOR and OPT-DECOR receivers cannot be implemented because the matrix $\mathbf{Q} = \mathbf{S}\mathbf{S}^\dagger$ is singular and has no inverse.

Comparing these results with those in Fig. 2 we see that the reduced spreading factor has degraded the performance of all receivers. However, the major impact is on the $\star$-LMMSE receivers, whose performance loss is about 4 dB, whereas the $\star$-MF receivers' performances are only affected by limited degradation (around 0.5 dB).

We think this is a consequence of the fact that the inverse matrix postmultiplication in the $\star$-LMMSE is more disrupting when we reduce the spreading factor below t since the matrix to invert, namely, $(\mathbf{S}\mathbf{S}^\dagger + (N_0/E_s)\mathbf{I}_t)$, becomes closer to singular at high SNR since $\mathbf{S}\mathbf{S}^\dagger$ is singular in this case.

The diagrams also show that the OPT-MF receiver loses about 1 dB from the joint LMMSE at FER$= 10^{-3}$. The ML receiver performance is not included among these results again because of the huge computational load required.

8. CONCLUSIONS

In this work we addressed the design of separate receivers for the multiuser multiple-access MIMO channel. These receivers have two linear interfaces mitigating separately the multiple-access and spatial interference and are helpful in situations where an existing multiuser receiver is going to be upgraded by a MIMO subsystem.

Assuming a given multiuser receiver, we designed a MIMO subsystem (i.e., a linear interface mitigating spatial interference) according to several criteria: plain matched filter, zero-forcing, linear minimum mean-square error, and optimized. The last linear interface is obtained by minimizing the mean-square error resulting from the assumption of a given multiuser detector (we considered the following: matched filter, decorrelator, and linear minimum mean-square error).

Simulation results show that the optimum performance is obtained when the multiuser detector is based on a plain matched filter (in our notation of eq. (5): $\mathbf{B} = \mathbf{S}^{\dagger}$).

The resulting performance loss with respect to the ML receiver depends on the system parameters and on the FER level considered. In the simulation results presented, the loss is around 1 dB and decreases by increasing the spreading factor.

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