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Spatial-Mode Selection based on Channel Mean Feedback for a Robust Joint Linear Precoder and Decoder MMSE Design

Nadia Khaled[1]
Interuniversity Micro-Electronics Center (IMEC)
Kapeldreef 75,
B-3001 Leuven Belgium
Email: nadia.khaled@imec.be

Geert Leus[2]
Delft University of Technology
Faculty of Electrical Engineering, Mathematics and Computer Science
Mekelweg 4,
2628 CD Delft The Netherlands
Email: leus@cas.et.tudelft.nl

Claude Desset, Hugo De Man[3]
Interuniversity Micro-Electronics Center (IMEC)
Kapeldreef 75,
B-3001 Leuven Belgium
Email: desset,deman@imec.be

Abstract — **The joint linear precoder and decoder Minimum Mean Squared Error (MMSE) design represents a low complexity yet powerful solution for spatial multiplexing MIMO systems. Its performance can be further boosted through optimally selecting the number of spatial streams to be used according to the available Channel State Information (CSI), so-called spatial-mode selection. The performance of both the latter MMSE design and the related spatial-mode selection criteria, however, critically depends on the availability of timely CSI at both transmitter and receiver. In practice, the latter assumption can be severely challenged, due to channel time variations that lead to imperfect CSI at the transmitter. State-of-the-art designs mistakenly use this imperfect CSI to design the linear precoder and rely on the receiver to reduce the induced degradation. We have alternatively proposed a robust Bayesian joint linear precoder and decoder solution that takes into account the uncertainty on the true channel, given the channel mean feedback at the transmitter. In this paper, we further improve the performance of our aforementioned robust design using a new spatial-mode selection criterion based on channel mean feedback. We also illustrate, via Monte-Carlo analysis, the robustness of the resulting improved design to channel time variations, which outperforms the state-of-the-art approach.**

I. Introduction

To enable spatial multiplexing MIMO systems, the joint linear precoder and decoder Minimum Mean Squared Error (MMSE) design has been proposed [1, 2]. It is a low complexity yet powerful design for applications, where the channel is slowly varying, such that the Channel State Information (CSI) can be made available at both sides of the transmission link. In fact, the design of [1, 2] exploits this CSI to optimally allocate power across the transmitted data streams in order to reduce the system's Bit-Error Rate (BER). To further minimize the joint linear precoder and decoder MMSE design BER performance, we have previously advocated to optimally select, based on the available CSI, the number of spatial multiplexing data streams to be transmitted. We have also shown that this so-called spatial-mode selection [8, 9] provides significant system BER improvement, thanks to the more efficient transmit power allocation and the better spatial diversity exploitation it enables. So far, however, both the joint linear precoder and decoder MMSE design and spatial-mode selection criteria have assumed perfect CSI.

Channel time variations can compromise the availability of such perfect timely CSI at both transmitter and receiver. Such channel variations occur due to the wireless terminal movement or due to the movement of objects in the propagation environment. At the receiver, channel estimation is carried out using the preamble prepended to the data payload. If we omit channel estimation errors and assume not too long bursts, one can reasonably assume perfect timely receiver CSI as data and preamble undergo the same channel. This is not the case at the transmitter side. In fact, whether the CSI is acquired through a feedback link from the receiver or through direct estimation using training from the receiver, there will always be a delay between the moment a channel realization is observed and the moment it is actually used by the transmitter. Combined with channel time-variations, this delay inevitably leads to imperfect CSI at the transmitter. This imperfect CSI is mistakenly used to calculate the linear precoder in the state-of-the-art joint linear precoder and decoder MMSE solution [14], which relies on the receiver to reduce the induced BER degradation.

As an alternative to the latter state-of-the-art approach, we have previously proposed a robust joint linear precoder and decoder design that takes into account the uncertainty on the true channel given the imperfect CSI at the transmitter [6]. The latter design applies a Bayesian approach, similar to those already proposed in other contexts such as beamforming for MISO systems [3] and space-time coded MIMO systems [4, 5], to spatial multiplexing scenarios. Our robust joint linear precoder and decoder MMSE design has been derived for a given number of spatial multiplexing streams which is arbitrarily chosen and fixed. In the present contribution, we introduce a new spatial-mode selection criterion that exploits the available imperfect CSI in order to enhance the performance of the latter design.

The rest of the paper is organized as follows: Section II introduces the data and channel mean feedback models. Based on that, both the state-of-the-art and our robust joint linear precoder and decoder MMSE designs are reviewed in Section III. In Section IV, we motivate and derive the proposed spatial-mode selection criterion based on channel mean feedback. Section V assesses the performance improvements, in terms of MMSE and BER, enabled by the proposed criterion. Finally, we draw some conclusions in Section VI.

Notations: In all the following, normal letters designate

[1]Also Ph.D. student at KULeuven, E.E. Dept., ESAT/INSYS.

[2]In part supported by NWO-STW under project DTC.5893 (VICI-SPCOM).

[3]Also Professor at KULeuven, E.E. Dept., ESAT/INSYS.

etters indicate vectors and boldface capitals represent matrices. $\mathbf{I}_p$ is the $p \times p$ identity matrix. Moreover, $trace(\mathbf{M})$, $[\mathbf{M}]_{i,j}$, $[\mathbf{M}]_{.,j}$, $[\mathbf{M}]_{.,1:j}$ respectively stand for the trace, the $(i,j)^{th}$ entry, the j^{th} column and the j first columns of matrix $\mathbf{M}$. $[x]^+$ refers to $\text{Max}(x, 0)$ and $()^H$ denotes the conjugate transpose of a vector or a matrix.

II. System model

A Data model

The spatial multiplexing MIMO system, under consideration, consists of a transmitter and a receiver, equipped with an M_T- and M_R-element antenna respectively. At the transmitter, the input symbol stream $s(n)$ is demultiplexed into $p \leq \text{Min}(M_R, M_T)$ independent streams, leading to an equivalent p-dimensional spatial symbol stream $\mathbf{s}(k)$. This spatial symbol stream $\mathbf{s}(k)$ is then passed through the linear precoder $\mathbf{T}$ before transmission through the M_T-element transmit antenna at rate $1/T$. At the receiver, the M_R complex baseband outputs from the M_R-element receive antenna sampled at rate $1/T$ are filtered by the linear decoder $\mathbf{R}$. The resulting p output streams conveying the detected spatial symbols $\hat{\mathbf{s}}(k)$ are then multiplexed and demodulated. For a flat-fading MIMO channel, the system equation is then given by:

$$\hat{\mathbf{s}}(k) = \mathbf{RHTs}(k) + \mathbf{Rn}(k) \tag{1}$$

where $\mathbf{n}(k)$ is the M_R-dimensional receive noise vector at time k and $\mathbf{H}$ is the $M_R \times M_T$ flat-fading channel matrix whose entries represent the complex channel gains from each transmit antenna to each receive antenna. In all the following, the time index k is dropped for clarity.

B Channel mean feedback model

Typically, a transmitter and receiver pair will communicate during multiple MAC frames. During each frame of duration T_{obs}, channel estimation is performed. Consequently, estimates of multiple channel realizations may be made available at one or both sides of the communication link, when a connection is setup. For simplicity, we assume that the time-varying channel is sampled uniformly with a period T_{obs} and we denote $\mathbf{H}(i)$ the channel estimate during the i^{th} frame. In the framework of linear precoder and decoder design, a straightforward and simple approach consists in retaining only the channel estimate $\mathbf{H}(i)$ corresponding to the current i^{th} frame to design the linear precoder $\mathbf{T}$ to be used during the next $(i+1)^{st}$ frame. The channel estimates corresponding to the previous frames are just dropped. Alternatively, a more advantageous approach may be to collect some of these available channel estimates, for instance $\{\mathbf{H}(l)\}_l$ with $l = (i-P)\dots i$, and use them in order to predict the channel $\mathbf{H}(i+1)$ during the frame to come [10].

In all the following, we assume that the channel estimation and the channel feedback link, if any [1], are error-free. Thus, during the $(i+1)^{st}$ frame, the *true* channel realization $\mathbf{H}(i+1)$ is known at the receiver but not at the transmitter. Instead, the transmitter possesses an imperfect channel information $\hat{\mathbf{H}}(i+1)$, corresponding to either the true channel state during the previous frame or a predicted channel value. The reason behind this unified notation lies in the fact that both imperfect CSIs can be described using the same channel mean feedback model, as subsequently explained. Under the assumption of dense scattering in the vicinity of both transmitter and receiver, the MIMO channel matrix $\mathbf{H}$ can be modeled as a complex matrix whose entries are i.i.d zero-mean complex Gaussian variables with common variance σ_h^2; $\mathbf{H} \sim \mathcal{N}(\mathbf{0}_{M_R \times M_T}, \sigma_h^2 \mathbf{I}_{M_R M_T})$. Just like $\mathbf{H}(i+1)$ and the outdated CSI $\mathbf{H}(i)$ are, it was shown in [11] that, for the linear P^{th}-order MMSE prediction filter herein considered, $\mathbf{H}(i+1)$ and the predicted CSI $\hat{\mathbf{H}}(i+1)$ are correlated realizations of the aforementioned complex Gaussian channel distribution. Thus, given the available imperfect CSI $\hat{\mathbf{H}}(i+1)$, we can characterize the unknown current CSI $\mathbf{H}(i+1)$ using the conditional channel mean feedback model introduced in [3], as follows:

$$\mathbf{H}(i+1) \sim \mathcal{N}(\rho \hat{\mathbf{H}}(i+1), \sigma_h^2 (1 - |\rho|^2) \mathbf{I}_{M_R M_T}) \tag{2}$$

where ρ is the common correlation between the coefficients of the true and the available imperfect CSI, defined as $\rho = E\{[\mathbf{H}(i+1)]_{i,j} [\hat{\mathbf{H}}(i+1)]_{i,j}^H\} / \sigma_h^2$. The latter correlation coefficient depends on the channel time-variation model as well as the nature of the available imperfect CSI. We subsequently instantiate the channel mean feedback model of (2) for the 2 considered scenarios namely the outdated CSI case and the predicted CSI case.

- **Outdated CSI model**:

$$\mathbf{H}(i+1) \sim \mathcal{N}(\rho \mathbf{H}(i), \sigma_h^2 (1 - |\rho|^2) \mathbf{I}_{M_R M_T}) \tag{3}$$

  where $\rho = \mathcal{R}(T_{obs})$ is the autocorrelation value of the i.i.d time-varying MIMO channel coefficients at a delay T_{obs}.

- **Predicted CSI model**:

$$\mathbf{H}(i+1) \sim \mathcal{N}(\rho \hat{\mathbf{H}}(i+1), \sigma_h^2 (1 - |\rho|^2) \mathbf{I}_{M_R M_T}) \tag{4}$$

  where ρ is the common correlation between the true and the predicted channel coefficients, given by [11] $\rho = \sqrt{\mathbf{r}^H \mathbf{R}^{-1} \mathbf{r}}$ with:

$$\begin{cases} [\mathbf{R}]_{p,q} & = \mathcal{R}(|p-q| T_{obs}) \qquad \{p,q\} \in [0, P] \\ [\mathbf{r}]_p & = \mathcal{R}(|p+1| T_{obs}) \end{cases} \tag{5}$$

From now on, unless explicitly mentioned, the unified channel mean feedback model of (2) will be used. In the latter model, the frame index $(i+1)$ is redundant and will be further dropped for notational simplicity.

III. A robust joint linear precoder and decoder MMSE solution

A The state-of-the-art approach

The state-of-the-art approach [14] mistakenly assumes that the imperfect CSI available at the transmitter, $\hat{\mathbf{H}}$, is perfect. It designs the precoder $\mathbf{T}$ presuming that the receiver has the same CSI and implements the corresponding MMSE decoder $\mathbf{R}$ according to [1, 2]. More specifically, the transmitter designs the linear precoder $\mathbf{T}$, assuming that $\mathbf{T}$ and $\mathbf{R}$ are *jointly* designed to minimize the sum mean squared error subject to a fixed average total transmit power P_T constraint as stated in:

$$\begin{cases} \text{Min}_{\mathbf{R},\mathbf{T}} & E_{\mathbf{s},\mathbf{n}} \left\{ \| \mathbf{s} - (\mathbf{R}\hat{\mathbf{H}}\mathbf{T}\mathbf{s} + \mathbf{R}\mathbf{n}) \|_2^2 \right\} \\ \text{subject to:} & E_s \cdot trace(\mathbf{T}\mathbf{T}^H) = P_T \end{cases} \tag{6}$$

[1] Depending on whether the CSI is acquired at the transmitter through feedback from the receiver or direct estimation.

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ssume uncorrelated data symbols of non-normalized average symbol energy E_s and zero-mean temporally and spatially-white complex Gaussian noise samples with common variance σ_n^2. Let $\hat{\mathbf{H}} = \hat{\mathbf{U}}\hat{\Sigma}\hat{\mathbf{V}}^H$ be the Singular Value Decomposition (SVD) of the available imperfect CSI, $\hat{\mathbf{H}}$. The linear precoder $\mathbf{T}$, solution to (6), was shown [1, 2] to be the transmit beamformer $\mathbf{T} = [\hat{\mathbf{V}}]_{.,1:p} \cdot \Sigma_T$, where Σ_t is the $(p \times p)$ diagonal power allocation matrix that determines the transmit power distribution among the p strongest spatial modes, represented by $\hat{\Sigma}_p = [\hat{\Sigma}]_{1:p,1:p}$, and is given by:

$$\begin{cases} \Sigma_T^2 = \left[\frac{\sigma_n}{\sqrt{E_s\lambda}}\hat{\Sigma}_p^{-1} - \frac{\sigma_n^2}{E_s}\hat{\Sigma}_p^{-2}\right]^+ \\ \text{subject to:} \qquad trace(\Sigma_T^2) = \frac{P_T}{E_s} \end{cases} \tag{7}$$

Correspondingly, the presumed [2] mean squared errors on the p spatial streams can be easily found to be the diagonal elements of the $(p \times p)$ error covariance matrix, $\mathbf{MSE}_p$:

$$\mathbf{MSE}_p = E_s(\mathbf{I}_p - \frac{\sqrt{E_s\lambda}}{\sigma_n}\hat{\Sigma}_p\Sigma_T^2)^2 + E_s\lambda\Sigma_T^2 \tag{8}$$

In reality, however, the receiver has the timely CSI, $\mathbf{H}$, and can form the matched MMSE receiver given by:

$$\mathbf{R} = \left(\mathbf{T}^H\mathbf{H}^H\mathbf{H}\mathbf{T} + \frac{\sigma_n^2}{E_s}\mathbf{I}_p\right)^{-1}\mathbf{T}^H\mathbf{H}^H \tag{9}$$

Clearly, this approach is suboptimal. This is why, capitalizing on the previously introduced imperfect CSI model, we have proposed an improved joint precoder and decoder MMSE solution that takes into account the uncertainty about the CSI due to channel time variations [6].

B Our robust approach

We assume that the transmitter knows the conditional distribution of the true channel $\mathbf{H}$ and the structure of the receiver $\mathbf{R}$ given by (9). Consequently, instead of the ideal [3] design criterion of (6), we have proposed [6] a novel robust linear precoder $\mathbf{T}$ designed to minimize the conditional [4] sum mean squared error given the outdated CSI, subject to a fixed average total transmit power constraint:

$$\begin{cases} \text{Min}_{\mathbf{T}} \qquad E_{\mathbf{H}|\hat{\mathbf{H}}}\left\{E_{\mathbf{s},\mathbf{n}}\left\{\| \mathbf{s} - (\mathbf{RHTs} + \mathbf{Rn}) \|_2^2\right\}\right\} \\ \qquad \text{subject to:} \qquad E_s \cdot trace(\mathbf{T}\mathbf{T}^H) = P_T \end{cases}$$

For tractability, we have approached the actual MMSE receiver of (9) by a zero-forcing receiver $\mathbf{R} = \left(\mathbf{T}^H\mathbf{H}^H\mathbf{H}\mathbf{T}\right)^{-1}\mathbf{T}^H\mathbf{H}^H$ while designing $\mathbf{T}$. Consequently, the general MMSE optimization problem has been reduced to:

$$\begin{cases} \text{Min}_{\mathbf{T}} \qquad E_{\mathbf{H}|\hat{\mathbf{H}}}\left\{E_{\mathbf{n}}\left\{trace(\mathbf{Rn}(\mathbf{Rn})^H)\right\}\right\} \\ \text{subject to:} \qquad E_s \cdot trace(\mathbf{T}\mathbf{T}^H) = P_T \end{cases} \tag{11}$$

Resorting to the Lagrange multiplier techniques to solve the above optimization problem, the cost function can be written as:

$$\mathcal{C} = trace\left(E_{\mathbf{H}|\hat{\mathbf{H}}}\left\{\sigma_n^2(\mathbf{T}^H\mathbf{H}^H\mathbf{H}\mathbf{T})^{-1}\right\} + \lambda E_s\mathbf{T}\mathbf{T}^H\right) \tag{12}$$

We have previously stated that, given the imperfect CSI, the true channel follows the complex normal distribution of (2). Thus, we can instantiate the true channel $\mathbf{H}$ as $\mathbf{H} = \hat{\mathbf{H}}_{eq} + \Delta$, where $\hat{\mathbf{H}}_{eq} = \rho\hat{\mathbf{H}}$ and Δ is the $\mathcal{N}\left(\mathbf{0}_{M_R \times M_T}, \sigma_h^2(1-|\rho|^2)\mathbf{I}_{M_R M_T}\right)$-distributed uncertainty on the true channel given the imperfect CSI. Let $\mathbf{T} = \mathbf{U}_T\Sigma_T^{rob}\mathbf{V}_T^H$ be the SVD of the precoder $\mathbf{T}$. On the one hand, it is clear that $\mathbf{V}_T$ does not alter the cost function of (12) so it can be simply set to identity. On the other hand, state-of-the-art literature shows that, given the equivalent channel $\hat{\mathbf{H}}_{eq} = \hat{\mathbf{U}}\hat{\Sigma}_{eq}\hat{\mathbf{V}}^H$, the optimal transmit strategy is to beamform into the p strongest eigenmodes of the mean channel i.e $\mathbf{U}_T = [\hat{\mathbf{V}}]_{.,1:p}$. Consequently, the optimal linear precoder and decoder pair $\{\mathbf{T},\mathbf{R}\}$, solution to (12), was shown to be [6]:

$$\begin{cases} \mathbf{T} = [\hat{\mathbf{V}}]_{.,1:p} \cdot \Sigma_T^{rob} \\ \mathbf{R} = \left(\mathbf{T}^H\mathbf{H}^H\mathbf{H}\mathbf{T} + \frac{\sigma_n^2}{E_s}\mathbf{I}_p\right)^{-1}\mathbf{T}^H\mathbf{H}^H \end{cases} \tag{13}$$

where Σ_T^{rob} is the $(p \times p)$ diagonal power allocation matrix that determines the transmit power distribution among the p strongest spatial modes of $\hat{\Sigma}_{eq}$ [5] and is given by [6]:

$$\Sigma_T^{rob} = \left(\frac{\sigma_n^2}{\lambda E_s}\left[\sigma_h^2(1-|\rho|^2)(p - M_R)\hat{\Sigma}_{eq}^{-4} + \left(1 + \sigma_h^2(1-|\rho|^2)trace(\hat{\Sigma}_{eq}^{-2})\right)\hat{\Sigma}_{eq}^{-2}\right]^+\right)^{1/4} \tag{14}$$

where λ is the Lagrange multiplier to be calculated to satisfy the power constraint. Furthermore, the corresponding conditional error covariance $\mathbf{MSE}_p^{rob}$, whose trace has been minimized as stated in (11) and (12), is defined as:

$$\mathbf{MSE}_p^{rob} = E_{\mathbf{H}|\hat{\mathbf{H}}}\left\{\sigma_n^2(\mathbf{T}^H\mathbf{H}^H\mathbf{H}\mathbf{T})^{-1}\right\} \tag{15}$$

Using the robust linear precoder solution of (13) and (14), the aforementioned conditional error covariance can be developed into:

$$\mathbf{MSE}_p^{rob} = \sigma_n^2\left[\sigma_h^2(1-|\rho|^2)(p - M_R)\hat{\Sigma}_{eq}^{-4} + \left(1 + \sigma_h^2(1-|\rho|^2)trace(\hat{\Sigma}_{eq}^{-2})\right)\hat{\Sigma}_{eq}^{-2}\right]\Sigma_T^{rob^{-2}} \tag{16}$$

Let $\Psi = \sigma_h^2(1 - |\rho|^2)(p - M_R)\hat{\Sigma}_{eq}^{-4} + (1 + \sigma_h^2(1 - |\rho|^2)trace(\hat{\Sigma}_{eq}^{-2}))\hat{\Sigma}_{eq}^{-2}$, the conditional error covariance matrix $\mathbf{MSE}_p^{rob}$ of (16) can be re-written as:

$$\mathbf{MSE}_p^{rob} = \sqrt{\lambda\sigma_n^2 E_s}\Psi\sqrt{[\Psi]^+} \tag{17}$$

IV. Spatial-Mode Selection based on channel mean feedback

The state-of-the-art joint linear precoder and decoder MMSE designs have been derived for a given number of spatial streams p which is arbitrarily chosen and fixed [1, 2]. These p streams will always be transmitted regardless of the power allocation policy that may, as highlighted by the $[]^+$ in (7) and (14), allocate no power to certain weak spatial modes. The data streams assigned to the latter modes are then lost, leading to a poor overall Bit-Error Rate (BER) performance. As the SNR increases, these initially disregarded modes will eventually be given power

[2]The pair $\{\mathbf{T},\mathbf{R}\}$ is assumed to be designed based on the same supposed-perfect imperfect CSI $\hat{\mathbf{H}}$.

[3]corresponding to the ideal case where both sides of the link have the same perfect timely CSI.

[4]on the true channel.

[5]For simplicity of notation, $\hat{\Sigma}_{eq}$ now refers to $[\hat{\Sigma}_{eq}]_{1:p,1:p}$.

able transmit power, leading to an inefficient power allocation strategy that detrimentally impacts the strong modes. Furthermore, these weakest modes will still exhibit the largest mean squared errors and BER contributions. Finally, It has been shown in [7] that the spatial mode gains exhibit decreasing diversity orders. This means that the weakest used mode sets the spatial diversity order exploited by the joint linear precoder and decoder MMSE design. The previous remarks highlight the influence of the choice of p on the transmit power allocation efficiency, the exhibited spatial diversity order and thus on the joint linear precoder and decoder MMSE designs' BER performance. Hence, we alternatively proposed to include p as a design parameter to be optimized according to the available channel knowledge for an improved system BER performance, which we referred to as *spatial-mode selection* [8]. We have proposed various selection criteria and shown the significant BER performance improvement they provide over state-of-the-art designs in [8, 9]. In our previous contributions, however, we have always assumed perfect timely CSI at both sides of the transmission link. In practice, due to channel time variations, this assumption can be severely challenged and consequently the performance of the previously proposed selection criterion can significantly degrade. Hence, in the present contribution, we investigate a scenario, where only channel mean feedback is available at the transmitter. We further derive a spatial-mode selection criterion that exploits this imperfect CSI to enhance the performance of our aforementioned robust joint linear precoder and decoder MMSE design.

Recalling the fact that the diagonals of $\hat{\Sigma}$ and $\hat{\Sigma}_{eq}$ contain singular values ordered in decreasing order, we can state that the diagonal elements of the previously introduced Ψ are monotonously increasing down the diagonal. Consequently, the examination of (17) shows that the conditional mean squared errors are uneven across p streams. Furthermore, the weakest p^{th} mode exhibits the largest conditional mean squared error and may be expected to dominate the BER performance of our robust joint linear precoder and decoder design. Consequently, we propose as the optimal number of spatial streams to be used, p_{opt}, the one that minimizes the mean squared error on the weakest used mode under a fixed spectral efficiency R constraint. We still assume the same symbol constellation across the spatial streams for a low-complexity joint linear precoder and decoder MMSE design. This symbol constellation, however, has to be adapted to the number of streams p in order to satisfy the fixed spectral efficiency R. Hence, the constellation size corresponding to a given number of spatial streams p will be denoted M_p and is given by $M_p = 2^{R/p}$. For a meaningful spatial-mode selection, we have enforced a fixed minimum distance for all used symbol constellations $\{M_p\}_p$. The proposed spatial-mode selection criterion based on the channel mean feedback can then be expressed as follows:

$$\begin{cases} \text{Min}_p & [\mathbf{MSE}_p^{rob}]_{p,p} \\ \text{subject to:} & p \times log_2(M_p) = R \end{cases} \tag{18}$$

The latter spatial-mode selection criterion can be further refined for the herein considered non-normalized square QAM constellations, through replacing $E_s = 2(M_p - 1)/3 = 2(2^{R/p} - 1)/3$ in the robust power allocation expression of (14).

As a reference, we similarly derive a spatial-mode selection for the state-of-the-art joint linear precoder and decoder design solution to (6). Contrarily to our new conditional spatial-mode

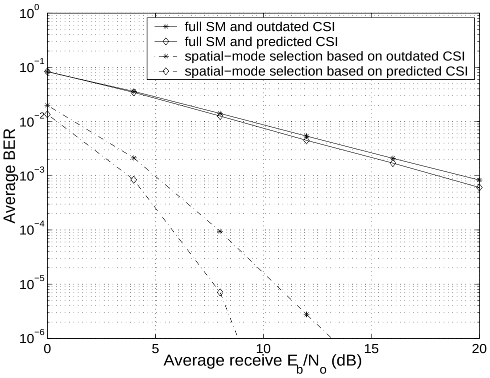

Figure 1: *Illustration of the performance of spatial-mode selection based on channel mean feedback for a (4,4) MIMO set-up, using the robust MMSE design, at spectral efficiency of* 8 *bits/s/Hz and normalized delay* $fd.T_{obs} = 0.1$

selection, this spatial-mode selection does not exploit the knowledge of the conditional distribution of the true channel, given the available imperfect CSI. Instead, consistently with the state-of-the-art linear precoder and decoder MMSE design, it assumes that the available imperfect CSI, $\hat{\mathbf{H}}$, is perfect and timely. As such, it exploits the presumed error covariance matrix $\mathbf{MSE}_p$ of (8). Consequently, the spatial-mode selection consistent with the state-of-the-art linear precoder and decoder MMSE design can be drawn as:

$$\begin{cases} \text{Min}_p & [\mathbf{MSE}_p]_{p,p} \\ \text{subject to:} & p \times log_2(M_p) = R \end{cases} \tag{19}$$

V. Performance results

In this section, we illustrate the improvements, in terms of average MMSE and BER, that the spatial-mode selection based on channel mean feedback provides to our robust linear precoder and decoder MMSE design, in presence of both outdated and predicted CSI at the transmitter. We further compare this performance to the straightforward approach that simply ignores the fact that the available CSI at the transmitter is imperfect. In order to do that, we use the well-known Jakes model [12] to instantiate realistic imperfect CSI models based on (2). Under the assumption of isotropic scattering and moving terminal, this model describes the channel time-correlation function as $\mathcal{R}(dT) = J_0(2\pi f_D dT)$, where $J_0(.)$ is the zero-th order Bessel function of the first kind and f_D is the Doppler frequency. In our simulations, we use the parameters which have been standardized for this model in the context of indoor WLANs [13] as it is a potential application for the joint linear precoder and decoder designs. In particular, we consider a Doppler frequency of 50 Hz. Finally, as aforementioned, the receiver possesses and uses perfect timely CSI to form the MMSE receiver of (9).

Figure 1 plots the BER performance of our robust MMSE design with and and without spatial-mode selection, for a $(4,4)$ MIMO set-up at a normalized delay $f_D T_{obs} = 0.1$, corresponding to a channel observation period T_{obs} equal to the Hiperlan II MAC frame length of 2 ms. It clearly shows that spatial-mode selection is beneficial in the design of the linear precoder $\mathbf{T}$, whether it is based on outdated CSI or a predicted CSI. Nevertheless, spatial-mode selection provides the largest BER

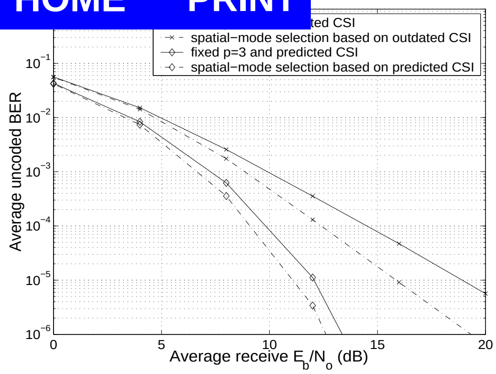

Figure 2: *Illustration of the performance of spatial-mode selection based on channel mean feedback for a (4,4) MIMO set-up, using the robust MMSE design, at spectral efficiency of* 12 *bits/s/Hz and normalized delay* $fd.T_{obs} = 0.1$

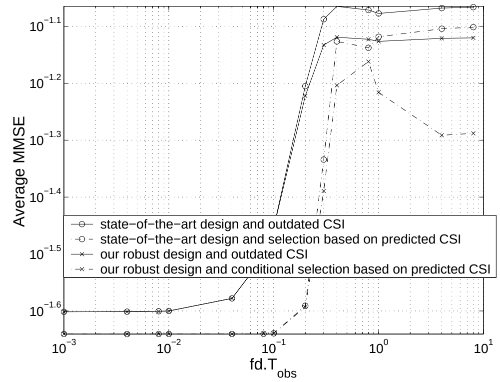

Figure 3: *Average MMSE versus the normalized delay for a (4,4) MIMO set-up with 3 streams at spectral efficiency of* 12 *bits/s/Hz,* $E_b/N_o = 20$ *dB and using a* 2^{nd}*-order linear MMSE predictor*

improvement, when it is combined with prediction. This is due to the fact that the used 2^{nd}-order linear MMSE predictor increases the correlation ρ between the available imperfect CSI $\hat{\mathbf{H}}$ and the true channel from 0.90 to 0.99, 0.90 corresponding to the outdated CSI case. As a result, prediction enables a more accurate spatial-mode selection and precoder design, which outperforms the precoder based on the outdated CSI, as illustrated in Figure 1. Full spatial multiplexing turns out to be the worst transmission approach. Hence, Figure 2 considers a better initial design, namely a robust design using only 3 data streams for a $(4, 4)$ MIMO set-up at spectral efficiency $R = 12$ bits/s/Hz. Still spatial-mode selection based on channel mean feedback is shown to improve the BER performance of our robust MMSE design. Moreover, the initial good choice of the number of streams $p = 3$ allows a better exploitation of the more accurate CSI provided by prediction. This explains the significant performance enhancement enabled by prediction in Figure 2, contrarily to Figure 1. Figure 3 further compares the MMSE performance of our robust design to that of the state-of-the-art design, with or without spatial-mode selection based on predicted CSI, over a large range of observation periods T_{obs} at a fixed average receive $E_b/N_o = 20$ dB. For normalized delays up to 10^{-1} corresponding to time correlations larger than 0.9, both designs exhibit the same average MMSE. However, as the delay increases and the time correlation gets low, the robust spatial-mode selection applied to our robust design outperforms the state-of-the-art design employing the non-robust spatial-mode selection of (19). This is due to the fact that the robust design as well as the related spatial-mode selection take into account the uncertainty around the true channel, due to channel time variations, in the design of the precoder $\mathbf{T}$.

VI. Conclusions

In this paper, we have proposed a spatial-mode selection based on channel mean feedback that improves the BER performance of the previously introduced robust joint linear precoder and decoder MMSE design. We have also shown that our robust approach outperforms the state-of-the-art approach in terms of MMSE and BER in slowly time-varying scenarios.

References

[1] H. Sampath, P. Stoica and A.J. Paulraj, "Generalized linear precoder and decoder design for MIMO channels using the weighted MMSE criterion", *IEEE Trans. on Communications* , Vol. 49, No. 12, Dec. 2001.

[2] A. Scaglione, P. Stoica, S. Barbarossa, G.B. Giannakis and H. Sampath, "Optimal designs for space-time linear precoders and decoders", *IEEE Trans. on Signal Processing*, Vol. 50, No. 5, pp. 1051-1064, May 2002.

[3] A. Narula, M.J. Lopez, M.D. Trott and G.W. Wornell, "Efficient use of side information in multiple-antenna data transmission over fading channels", *IEEE. JSAC*, Vol. 16, No. 8, pp. 1423-1436, Oct. 1998.

[4] G. Jöngren, M. Skoglund and B. Ottersten, "Combining beamforming and orthogonal space-time block coding", *IEEE Trans. on Information theory*, Vol. 48, No. 3, Mar. 2002.

[5] S. Zhou and G.B. Giannakis, "Optimal transmitter eigenbeamforming and space-time block coding based on channel mean feedback", *IEEE Trans. on Communications*, Vol. 50, No. 10, pp. 2599-2613, Oct. 2002.

[6] N. Khaled, G. Leus, C. Desset and H. De Man, "A robust joint linear precoder and decoder MMSE design for slowly time-varying MIMO channels", *IEEE ICASSP*, 2004 (to appear).

[7] J.B. Andersen, "Array gain and capacity for known random channels with multiple elements arrays at both ends", *IEEE JSAC*, Vol. 18, No. 11, pp. 2172-2178, Nov. 2000.

[8] N. Khaled, S. Thoen, L. Deneire and H. De Man, "Spatial-mode selection for the joint transmit receive MMSE design over flat-fading MIMO channels", *IEEE SPAWC*, Rome, Italy, June 2003.

[9] N. Khaled, C. Desset, S. Thoen and H. De Man, "On spatial-mode selection for the joint transmit and receive MMSE design", *IEEE ICC*, 2004 (to appear).

[10] A. Duel-Hallen, S. Hu and H. Hallen, "Long-range prediction of fading signals", *IEEE Signal Processing Magazine*, Vol. 17, No. 3, pp. 62-75, May 2000.

[11] S. Zhou and G.B. Giannakis, "How accurate channel prediction needs to be for transmit-beamforming with adaptive modulation over Rayleigh MIMO channels?", *IEEE Trans. on Wireless Communications*, 2004 (to appear).

[12] W.C. Jakes, "Microwave Mobile Communications", *IEEE Press*, 1993.

[13] http://www.hiperlan2.com.

[14] G. Lebrun, T. Ying and M. Faulkner, "MIMO transmission over a time-varying channel using SVD", *IEEE Globecom*, Vol. 1, pp. 414-418, Nov. 2002.