Optimization Criteria for Linear Precoding in Flat Fading TDD-MIMO Downlink Channels with Matched Filter Receivers

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***Abstract*— We propose a *time division duplex - multiple input multiple output* (TDD-MIMO) system with receiver matched to the transmit filter and channel, leading to a linear transmission system which diagonalizes the MIMO channel into its eigenspace similar to *joint transmit and receive filter optimization* (joint TX/RX optimization), but without the need to perform the optimization at both sides of the link or feedback. We investigate different optimization criteria well known from linear precoder design and joint TX/RX optimization: *transmit matched filter* (TxMF), *transmit zero-forcing filter* (TxZF), and *transmit Wiener filter* (TxWF).**

I. Introduction

Joint TX/RX optimization is a well researched and understood approach for MIMO systems [1], [2], [3], [4], [5], [6], [7], [8], where the receive and transmit filters result from one optimization. Consequently, the transmitter and receiver have to perform the optimization independently or one side has to feed back the result of the optimization to the other side of the link. Suboptimum solutions for the joint TX/RX optimization are *receive* (RX) only and *transmit* (TX) only processing. RX processing (e. g. [9]) requires a transmit filter which is *a priori* known to the receiver, whereas TX processing designs a precoding filter with the *a priori* knowledge of the receive filter (e. g. [10], [11]). Both approaches share the advantage that only one side of the link has to optimize its filter and the other side simply follows the *a priori* defined design rule.

TX processing is especially advantageous for TDD systems in the downlink, since the transmitting *base station* (BS) can re-use the uplink channel estimation for the design of the downlink precoding filter and the *mobile station* (MS) is simplified compared to joint TX/RX or RX processing. Conventionally, the receiver for a TX processing system is assumed to be fixed [11] or matched to the channel [10] to end up with a MS as simple as possible.

We propose a MIMO system with TX processing, where the receive filter in the MS is matched not only to the channel but also to the precoding filter which has been proposed only for the *prerake* or TxMF in [12] up to now. With this system constraint the receiver is also part of the optimization process and changes with the transmitter design, however, it is bound to be the matched filter. Consequently, we will denote the proposed MIMO processing scheme as *semi-joint optimization*. This assumption is advantageous in two ways. First of all, the pilot symbols necessary for channel estimation at the MS can be transmitted time multiplexed with the data and have to be passed through the precoding filter. Therefore, the MS estimates the combination of the precoding filter and the channel together with the imperfections of the transmission chain, e. g. calibration errors, which are reduced by the matched filter.
Secondly, we end up with a decomposition of the channel in its eigenmodes similar to joint TX/RX optimization although the receiver only applies a matched filter. This diagonalization of the channel provides good conditions for spatial multiplexing: due to the diagonalization of the MIMO channel there is no *inter-stream-interference* (ISI) between parallel data streams.

We will derive and compare the following precoding filters for the proposed MIMO system which all share a transmit power constraint: the *matched-filter* (MF) resulting from a receive *signal to noise ratio* (SNR) maximization, the *zero-forcing filter* (ZF) which suppresses interference completely, and the *Wiener filter* (WF) minimizing the *mean square error* (MSE). In all of these cases we apply two approaches: in the first we keep the used modulation scheme fixed and identical for all transmitted data streams while we consider adaptive modulation in the second approach.

The paper is organized as follows. The system model is described in Section II. Section III and IV explain joint TX/RX optimization and the new proposed semi-joint optimization, respectively. In Section V both approaches are extended with adaptive modulation, where Section VI provides some simulation results. A conclusion is given in Section VII.

II. MIMO System Model

The data $\boldsymbol{s}[k] \in \mathbb{C}^B$ are filtered by the precoder $\boldsymbol{F} \in \mathbb{C}^{N\times B}$ at the BS to form the transmit signal. In the following, we assume that all transmit filters use the whole available transmit power P_t, i.e.

$$\mathrm{E}\left\{\|\boldsymbol{F}\boldsymbol{s}[k]\|_2^2\right\} = P_\mathrm{t}.$$

All considerations are based on the downlink from the BS to the MS over a frequency flat MIMO channel. After propagation over the MIMO channel $\boldsymbol{H} \in \mathbb{C}^{M\times N}$ with N transmit and M receive antenna elements and perturbation by the noise $\boldsymbol{n}[k]$, the received signal is passed through the linear receive filter $\boldsymbol{G}$ leading to the estimate (cf. Fig. 1)

$$\hat{\boldsymbol{s}}[k] = \boldsymbol{GHFs}[k] + \boldsymbol{Gn}[k]. \tag{1}$$

The spatial covariance matrix of the noise is denoted as $\boldsymbol{R}_n$ while the spatial covariance matrix of the sigal is denoted as $\boldsymbol{R}_s$ (and will be restricted to $\boldsymbol{R}_s \equiv \mathbf{1}$ in the following). We restrict ourselves to transmitting a constant data rate of b bits per channel use over B independent data streams with transmit power constraint P_{t}. Furthermore, we restrict to MIMO systems with $M \geq N$ and $B \leq N$.

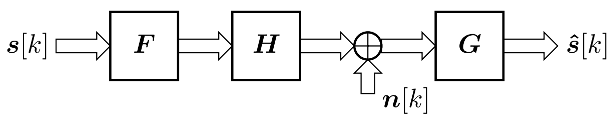

Fig. 1. MIMO System with Receiver Matched to Precoder and Channel

All linear precoders and receivers in the remainder of this paper can be expressed as function of the eigensystem of the following matrix product

$$\boldsymbol{H}^{\mathrm{H}}\boldsymbol{R}_n^{-1}\boldsymbol{H} = [\boldsymbol{V}\ \tilde{\boldsymbol{V}}]\begin{pmatrix} \boldsymbol{\Lambda} & \mathbf{0} \\ \mathbf{0} & \tilde{\boldsymbol{\Lambda}} \end{pmatrix}[\boldsymbol{V}\ \tilde{\boldsymbol{V}}]^{\mathrm{H}}, \tag{2}$$

where the matrices $\boldsymbol{\Lambda}$ and $\boldsymbol{V}$ contain the dominant (non-zero) eigenvalues and the corresponding eigenvectors. We assume that the eigenbase in $\boldsymbol{V}$ and $\boldsymbol{\Lambda}$ is sorted such, that in $\boldsymbol{\Lambda} = \mathrm{diag}\{\lambda_1, \lambda_2, \ldots, \lambda_N\}$ we have $\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_N$.

III. Joint Linear TX/RX Optimization

The idea of joint TX/RX optimization is to perform a co-operative design of the linear precoder and the linear receiver. It is intuitively clear that this approach will obtain the best performance of the linear signal processing methods with respect to the chosen optimization criterion.

In the following we will present the optimizition problems and the mathematical solution of each approach, where we omit the mathematical derivation for compactness. The computations can be found in [8].

A. The Joint Matched Filter

Maximizing the SNR at the receiver via a joint optimization of the linear transmitter $\boldsymbol{F}$ and the linear receiver $\boldsymbol{G}$ leads to the *joint MF* (JointMF) design. For the data model provided in Section II the maximization of the cross-correlation after the receiver for a precoder $\boldsymbol{F}$ and a receiver $\boldsymbol{G}$ under the transmit power constraint can be achieved with the following constrained optimization

$$\{\boldsymbol{F}_{\mathrm{MF}}^{\mathrm{jt}}, \boldsymbol{G}_{\mathrm{MF}}^{\mathrm{jt}}\} = \underset{\{\boldsymbol{F},\boldsymbol{G}\}}{\mathrm{argmax}} \frac{\left|\mathrm{E}\left\{\hat{\boldsymbol{s}}^{\mathrm{H}}[k]\boldsymbol{s}[k]\right\}\right|^2}{\mathrm{E}\left\{\|\boldsymbol{s}[k]\|_2^2\right\}\mathrm{E}\left\{\|\boldsymbol{Gn}[k]\|_2^2\right\}} \quad \text{s.t.} \quad \mathrm{tr}\left(\boldsymbol{FR}_s\boldsymbol{F}^{\mathrm{H}}\right) = P_{\mathrm{t}}, \tag{3}$$

where the cost function of the minimization is the SNR at the output of the receive filter. The solution for the joint MF computes as

$$\boldsymbol{F}_{\mathrm{MF}}^{\mathrm{jt}} = \boldsymbol{V}\cdot\mathrm{diag}\{P_{\mathrm{t}}, 0, \ldots, 0\} \quad \text{and} \tag{4}$$

$$\boldsymbol{G}_{\mathrm{MF}}^{\mathrm{jt}} = \mathrm{diag}\{\beta, 0, \ldots, 0\}\cdot\boldsymbol{V}^{\mathrm{H}}\boldsymbol{H}^{\mathrm{H}}\boldsymbol{R}_n^{-1}, \tag{5}$$

where $\beta = \lambda_1\left((P_{\mathrm{t}}\lambda_1+1)^{-1} - (P_{\mathrm{t}}\lambda_1+1)^{-2}\right)$, that is the scalar in Eq. (5) is chosen such, that the MSE is minimized. Note, that the joint MF always provides a rank 1 transmission, i.e. only the dominant eigenvector of $\boldsymbol{H}^{\mathrm{H}}\boldsymbol{R}_n^{-1}\boldsymbol{H}$ is used.

B. The Joint Zero-forcing Filter

The *joint ZF* (JointZF) approach performs a cooperative design of the linear precoder and linear receiver that eliminates the ISI and establishes the same path attenuation on each substream while simultaneously minimizing the MSE between the symbols $\boldsymbol{s}[k]$ and $\hat{\boldsymbol{s}}[k]$ under the transmit power constraint. The optimization reads as

$$\{\boldsymbol{F}_{\mathrm{ZF}}^{\mathrm{jt}}, \boldsymbol{G}_{\mathrm{ZF}}^{\mathrm{jt}}\} = \underset{\{\boldsymbol{F},\boldsymbol{G}\}}{\mathrm{argmin}}\,\mathrm{E}\left\{\|\boldsymbol{s}[k]-\hat{\boldsymbol{s}}[k]\|_2^2\right\} \quad \text{s.t.} \quad \boldsymbol{GHF} = \mathbf{1} \quad \text{and} \quad \mathrm{tr}\left(\boldsymbol{FR}_s\boldsymbol{F}^{\mathrm{H}}\right) = P_{\mathrm{t}}. \tag{6}$$

With the Lagrangian method, we find the joint ZF solution

$$\boldsymbol{F}_{\mathrm{ZF}}^{\mathrm{jt}} = \sqrt{\frac{P_{\mathrm{t}}}{\mathrm{tr}(\boldsymbol{\Lambda}^{-1})}}\boldsymbol{V}\boldsymbol{\Lambda}^{-1/4} \quad \text{and} \tag{7}$$

$$\boldsymbol{G}_{\mathrm{ZF}}^{\mathrm{jt}} = \sqrt{\frac{\mathrm{tr}(\boldsymbol{\Lambda}^{-1})}{P_{\mathrm{t}}}}\boldsymbol{\Lambda}^{-3/4}\boldsymbol{V}^{\mathrm{H}}\boldsymbol{H}^{\mathrm{H}}\boldsymbol{R}_n^{-1}. \tag{8}$$

Note, that the joint ZF does not switch off any data stream. Thus, the joint ZF always leads to a rank B transmission.

C. The Joint Wiener Filter

The minimization of the MSE between the transmitted symbols $\boldsymbol{s}[k]$ and the estimates $\hat{\boldsymbol{s}}[k]$ by a cooperative design of the linear precoder $\boldsymbol{F}$ and the linear receiver $\boldsymbol{G}$ leads to the *joint WF* (JointWF) solution with the optimization problem

$$\{\boldsymbol{F}_{\mathrm{WF}}^{\mathrm{jt}}, \boldsymbol{G}_{\mathrm{WF}}^{\mathrm{jt}}\} = \underset{\{\boldsymbol{F},\boldsymbol{G}\}}{\mathrm{argmin}}\,\mathrm{E}\left\{\|\boldsymbol{s}[k]-\hat{\boldsymbol{s}}[k]\|_2^2\right\} \quad \text{s.t.} \quad \mathrm{tr}\left(\boldsymbol{FR}_s\boldsymbol{F}^{\mathrm{H}}\right) = P_{\mathrm{t}}. \tag{9}$$

The solution for the joint WF can be computed as

$$\boldsymbol{F}_{\mathrm{WF}}^{\mathrm{jt}} = \boldsymbol{V}\boldsymbol{\Phi}_f \quad \text{and} \quad \boldsymbol{G}_{\mathrm{WF}}^{\mathrm{jt}} = \boldsymbol{\Phi}_g\boldsymbol{V}^{\mathrm{H}}\boldsymbol{H}^{\mathrm{H}}\boldsymbol{R}_n^{-1} \tag{10}$$

where $\boldsymbol{\Phi}_f$ and $\boldsymbol{\Phi}_g$ are positive semi-definite diagonal matrices

$$\boldsymbol{\Phi}_f^2 = \left(\mu^{-1/2}\boldsymbol{\Lambda}^{-1/2} - \boldsymbol{\Lambda}^{-1}\right)_+ \tag{11}$$

$$\boldsymbol{\Phi}_g^2 = \left(\mu^{1/2}\boldsymbol{\Lambda}^{-1/2} - \mu\boldsymbol{\Lambda}^{-1}\right)_+\boldsymbol{\Lambda}^{-1}. \tag{12}$$

Here the parameter μ has to be chosen to fulfill the transmit power constraint $\mathrm{tr}(\boldsymbol{\Phi}_f^2) = P_{\mathrm{t}}$. The operator $(x)_+$ is equivalent to $\max\{0, x\}$.

Note, that the joint WF converges to the joint MF solution for very low SNR, while it converges to the joint ZF solution for infinitely high SNR. Since the joint MF transmits only one data stream over the dominant eigenmode of the channel and the joint ZF always uses the B strongest eigenmodes of the channel for data transmission, the joint WF approach successively increases the number of used eigenmodes with increasing SNR. This behavior can also be recognized in the solution of $\boldsymbol{\Phi}_g$ where the operator $(\bullet)_+$ switches off these data streams, where the matrix entries are less than zero. The power allocation is accomplished such, that the weakest eigenmodes of the channel are neglected, while in the remaining eigenmodes more power is allocated in the weaker eigenmodes to minimize the MSE.

IV. Semi-Joint Linear Optimization

The joint TX/RX optimization represents the optimum approach that can be achieved with linear transmit/receive processing in terms of the mentioned optimization criterion. The big disadvantage of the joint TX/RX optimization is the computational complexity. Since the design of the linear precoder as well as the linear receiver evolve from one joint optimization approach, either both sides of the communication link have to perform the optimization, or the result of the optimization is computed at one side of the communication link for the price of having to transmit the optimization result to the other side of the communication link.
If neither the possibility of feedback nor sufficient computational resources at both sides of the link are available, the joint TX/RX optimization approach is not applicable. One possibility to overcome this dilemma is to consider a transmission approach where one side of the communication link is simplified with respect to the computational complexity, i.e. a restricted receiver structure.

In the following we will focus on a MIMO system where we assume a simplified receiver structure such, that the receive filter $\boldsymbol{G}$ is a matched-filter, not only to the channel $\boldsymbol{H}$ but also to the precoding filter $\boldsymbol{F}$. Note, that we have to allow for a scalar degree of freedom $g \in \mathbb{R}$ to correct the signal amplitude. This leads the the linear receive filter $\boldsymbol{G} = g(\boldsymbol{R}_n^{-1}\boldsymbol{H}\boldsymbol{F})^{\mathrm{H}}$. See the Fig. 2. This method provides two further advantages:

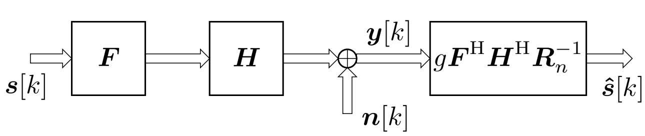

Fig. 2. Linear TX and RX processing with restricted receiver structure.

First, the pilot symbols necessary for channel estimation at the receiver can be transmitted time multiplexed with the data and are passed through the precoding filter. Therefore, the receiver estimates the combination of precoding filter and channel including the imperfections of the transmission chain. Secondly, we end up with a decomposition of the channel $\boldsymbol{H}$ in its eigenmodes similar to joint TX/RX optimization[1]. This diagonalization of the channel provides good conditions for spatial multiplexing: due to the diagonalization of the MIMO channel there is no ISI between parallel transmitted data streams.
For compactness we only give the optimization problem and the mathematical solution in this paper. The complete computations can be found in [13].

A. The Semi-Joint MF

Maximizing the cross-correlation at the receive filter output for the system in Fig. 2 with transmit power constraint and special restriction of the linear receiver to be the matched filter of the previous transmission chain we can rewrite the optimization of Fig. 3 as

$$\boldsymbol{F}_{\mathrm{MF}} = \underset{\boldsymbol{F}}{\operatorname{argmax}} \operatorname{tr}(\boldsymbol{R}_s \boldsymbol{F}^{\mathrm{H}} \boldsymbol{H}^{\mathrm{H}} \boldsymbol{R}_n^{-1} \boldsymbol{H} \boldsymbol{F} \boldsymbol{R}_s) \quad \text{s.t.} \quad \operatorname{tr}(\boldsymbol{F}\boldsymbol{R}_s\boldsymbol{F}^{\mathrm{H}}) = P_{\mathrm{t}}. \tag{13}$$

We obtain the solution using the Lagrangian function as

$$\boldsymbol{F}_{\mathrm{MF}} = [\sqrt{P_{\mathrm{t}}}\boldsymbol{v}_{\max}, \boldsymbol{0}], \tag{14}$$

where $\boldsymbol{v}_{\max}$ denotes the eigenvector of $\boldsymbol{H}^{\mathrm{H}}\boldsymbol{R}_n^{-1}\boldsymbol{H}$ belonging to the largest eigenvalue. Computing the scalar degree of freedom g as scalar WF to minimize the MSE gives

$$g_{\mathrm{MF}} = \frac{1}{P_{\mathrm{t}}\lambda_1 + \sigma_n^2}. \tag{15}$$

Note, that the semi-joint MF also transmits only one data stream as in the case of the joint MF. Also note, that the Joint MF and the semi-joint MF with scalar WF are identical.

B. The Semi-Joint ZF

Eliminating the ISI where we simultaneously minimize the MSE with fixed receiver structure and transmit power constraint can be expressed as

$$\{\boldsymbol{F}_{\mathrm{ZF}}, g_{\mathrm{ZF}}\} = \underset{\{\boldsymbol{F}, g\}}{\operatorname{argmin}}\, g^{-1} \quad \text{s.t. } \operatorname{tr}\left(\boldsymbol{F}^{\mathrm{H}}\boldsymbol{R}_s\boldsymbol{F}\right) = P_{\mathrm{t}} \quad \text{and } g\boldsymbol{F}^{\mathrm{H}}\boldsymbol{H}^{\mathrm{H}}\boldsymbol{R}_n^{-1}\boldsymbol{H}\boldsymbol{F} = \boldsymbol{1}. \tag{16}$$

The solution with the Lagrangian function reads as

$$\boldsymbol{F}_{\mathrm{ZF}} = \sqrt{\frac{P_{\mathrm{t}}}{\operatorname{tr}(\boldsymbol{\Lambda})}}\boldsymbol{V}\boldsymbol{\Lambda}^{-1/2} \quad \text{and} \quad g_{\mathrm{ZF}} = \frac{\operatorname{tr}(\boldsymbol{\Lambda})}{P_{\mathrm{t}}}. \tag{17}$$

The semi-joint ZF approach achieves a perfect ISI elimination and the whole transmission chain between the symbols $\boldsymbol{s}[k]$ and $\hat{\boldsymbol{s}}[k]$ is reduced to the identity matrix. Note, that the semi-joint ZF approach does not switch off eigenmodes of the channel, as in the case of the joint ZF approach.

C. The Semi-Joint WF

Minimizing the MSE between the filter output $\hat{\boldsymbol{s}}[k]$ and the signal $\boldsymbol{s}[k]$ with the special choice of a MF receiver leads to the semi-joint WF solution (cf. Fig. 1). The optimization reads as

$$\{\boldsymbol{F}_{\mathrm{ZF}}, g_{\mathrm{ZF}}\} = \underset{\{\boldsymbol{F}, g\}}{\operatorname{argmin}}\, \mathrm{E}\left\{\|\boldsymbol{s}[k] - \hat{\boldsymbol{s}}[k]\|_2^2\right\} \quad \text{s.t.} \quad \operatorname{tr}\left(\boldsymbol{F}^{\mathrm{H}}\boldsymbol{R}_s\boldsymbol{F}\right) = P_{\mathrm{t}}. \tag{18}$$

[1]Note, that other receiver concepts, like ZF, also diagonalize the MIMO channel. However, since the MF already is sufficient to diagonalize the channel we chose it due to its simplicity with respect to the computational complexity.

We obtain the solution using the Lagrangian function as

$$\boldsymbol{F}_{\mathrm{WF}} = \boldsymbol{V}\boldsymbol{\Lambda}^{-1}\boldsymbol{A}\frac{\mathrm{tr}(\boldsymbol{A})}{2\,\mathrm{tr}(\boldsymbol{A}-\boldsymbol{A}^2)} \quad \text{with} \quad \boldsymbol{A} = \left(\boldsymbol{1} - \epsilon\boldsymbol{\Lambda}^{-1}\right)_+, \tag{19}$$

where ϵ has to be chosen to fulfill the power constraint utilizing numerical optimization. Note, that the semi-joint WF converges to the semi-joint MF for low SNR and to the semi-joint ZF for hight SNR. Also note, that the semi-joint WF solution has the same property of the joint WF to successively increase the number of used data streams with increasing SNR.

D. Remarks

Note, that all precoding filters (joint and semi-joint) can be decomposed into $\boldsymbol{F} = \boldsymbol{V}\boldsymbol{D}$, where $\boldsymbol{V}$ is the eigenspace of the channel and $\boldsymbol{D}$ is a diagonal matrix. Moreover, note, that the derivation of all of the above mentioned precoders is independent of the chosen modulation schemes. Consequently, the assumed data rate of b bits per channel use can be achieved by distributing the bits onto the allocated, parallel data streams by appropriate modulation schemes. The simplest approach is to uniformly distribute the b bits onto the M data streams and to use the same modulation alphabet for each data stream.

V. Adaptive Modulation

A more sophisticated approach is to distribute the b bits onto the B data streams according to an additional optimization criterion which will allocate a higher data rate onto stronger data streams. This consideration leads to adaptive modulation. Since the channel is diagonalized and the weightings of each eigenmode is known from the computation of the precoding filter it is possible to compute the SNR of each eigenmode for the actual channel realization. Since the SNR and weighting h_i is known, it is now possible to a-priori compute the *bit-error probability* p for each data stream for a given modulation alphabet as [14]

$$p_i = f\left(\mathrm{SNR}_i, h_i, \mathcal{M}_i\right), \tag{20}$$

where p_i, SNR_i, h_i, and $\mathcal{M}_i$ denote the bit-error probability, the SNR, the weighting of the channel and the modulation alphabet of data stream i, respectively. The desired data rate of b bits per channel use is achieved by distributing the b bits onto the B data streams with appropriate modulation schemes where the average BER over all data streams of the actual channel realization can be minimized in an optimization as

$$\min_{\{\mathcal{M}_i\}} \sum_i f\left(\mathrm{SNR}_i, h_i, \mathcal{M}_i\right) \log_2 |\mathcal{M}_i|, \tag{21}$$

where $\log_2 |\mathcal{M}_i|$ computes the number of bits that are contained in modulation alphabet $\mathcal{M}_i$.

In the following, adaptive modulation is applied such that for each modulation set $\{\mathcal{M}_i\}$, which in sum provides a transmission rate of b bits per channel use, the channel weightings h_i and the SNR_i are computed and the optimization of Eq. (21) is evaluated. Note, that this does not require the complete computation of the filter pair $\boldsymbol{F}$ and $\boldsymbol{G}$. Contrary, TX-only processing results in ISI which makes adaptive modulation computationally prohibitive (similar to RX-only processing).

VI. Simulation Results

The uncoded BER performance of the joint TX/RX optimization, the semi-joint optimization, and TX only optimization (with $\boldsymbol{G} = \boldsymbol{1}$) is shown in Fig. 3. The signal $\boldsymbol{s}[k]$ is transmitted over a flat fading 4×4 MIMO system, where all entries of $\boldsymbol{H}$ are complex Gaussian i.i.d with zero mean and unit variance, and superimposed by complex Gaussian noise with zero mean and variance σ_n^2. We assume a fixed data rate of 8 bits per channel use with fixed QPSK modulation.

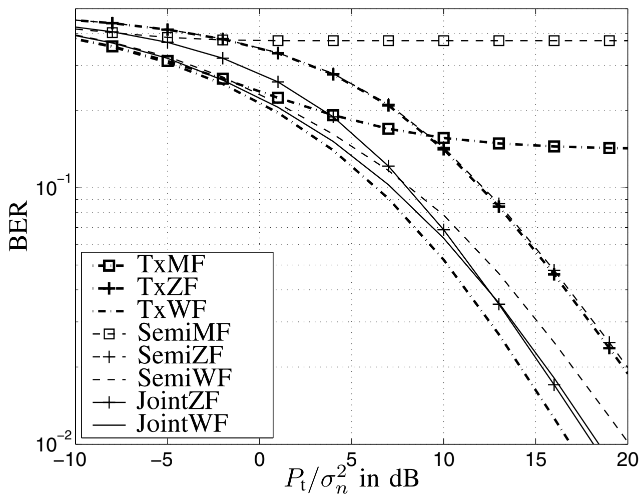

Fig. 3. Comparison of the different transmission strategies respect to the BER as function of the transmit SNR in dB for fixed modulation.

Since we assume a fixed data rate of 8 bits per channel use we always have to transmit all 4 data streams. The MF strategies are thus saturating: the TxMF because of the neglected interference, the semi-joint MF and joint MF because of a rank 1 transmission situation due to the optimization.
The WF strategies obtain the minimum MSE as required by the optimization, where the joint WF obtains the smallest MSE of all WF strategies. However, plotting the BER over the SNR shows that the computational extensive approaches like the joint WF and the semi-joint TxWF achieve only a comparable performance as the TxWF. This is due to the fixed modulation scheme and the variable number of allocated data streams in the case of JointWF and SemiWF.

Giving up the assumption of a fixed modulation scheme and only demanding a data rate of 8 bits per channel use produces the BER curves in Fig. 4, where only the ZF and WF curves are shown.
The TxWF curve does not change compared to Fig. 3. Since the channel is not diagonalized in this case, an a-priori computation of the BER is highly complicated. Thus adaptive modulation is not applied in case of TX-only optimization. The joint and the semi-joint curves achieve a huge performance boost, they even exploit a higher order of diversity when applying adaptive modulation. In channel realizations where one or more eigenmodes are weak, these eigenmodes are not used and the data is re-allocated onto the remaining stronger eigenmodes. Since the number of antennas remains constant,

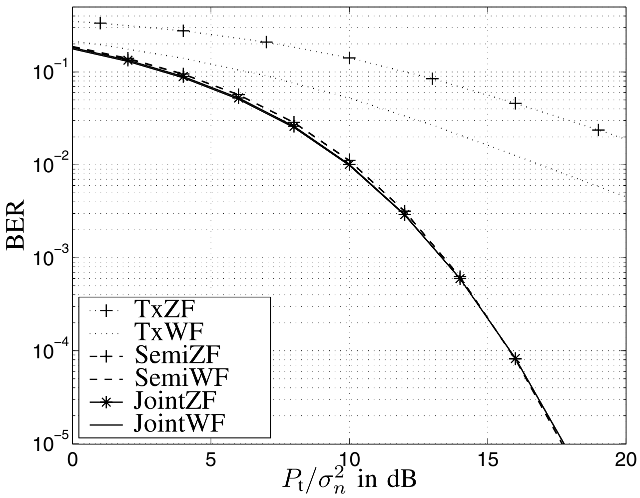

Fig. 4. Comparison of the different WF transmission strategies with respect to the BER as function of the transmit SNR with adaptive modulation.

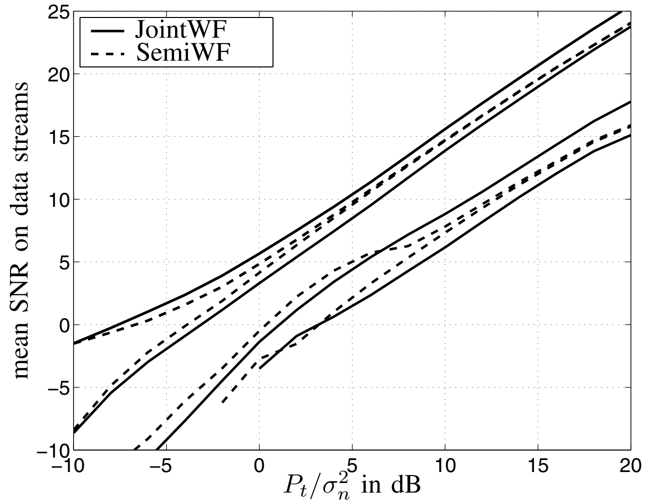

Fig. 5. Mean SNR on the data streams for JointWF and SemiWF. Data stream 1 has highest SNR, data stream 2 has second highest SNR, and so on.

the order of diversity is increased.

Note, that the proposed semi-joint optimization approaches have comparable BER performance as the joint optimization approaches when applying adaptive modulation, however, at at reduced computational complexity. Also note, that the proposed semi-joint optimization approaches even outperform the joint optimization for high SNR (> 15dB). Fig. 5 shows the mean SNR of the used data streams in the case of the joint WF and the semi-joint WF, where in each case data stream 1 has highest SNR, data stream 2 has second highest SNR, and so on, due to an ordered EVD. In the whole SNR range the strongest eigenmode of the joint WF has always a higher mean SNR compared to the strongest eigenmode of the semi-joint WF. At low and medium SNR range the data is mostly put into the strongest or the two strongest eigenmodes. In this case it is advantageous if the eigenmode containing the biggest portion of the data has a higher SNR. However, at high SNR ranges the solution of the joint and semi-joint WF with adaptive modulation tend to uniformly distribute the data onto all eigenmodes. In this case the data stream with the lowest mean SNR is limiting the BER performance. Since the 4th eigenmode of the joint WF has a lower mean SNR compared to the 4th eigenmode of the semi-joint WF, the BER performance of the joint WF is suffering from this effect at high SNR.

VII. Conclusion

In this paper we have proposed a new linear transmission strategy with a simple MF receiver structure and a precoder optimization according to the matched filter, zero-forcing, and minimum mean-square error principle. This new transmission concept accomplishes a diagonalization of the MIMO channel into its eigenmodes, similar to a joint TX/RX optimization, however, at a much lower computational cost for the receiver side. It has further been shown that with respect to the BER the proposed system concept has comparable performance as the joint TX/RX optimization scheme in the case of adaptive modulation. At high SNR the new transmission concept even outperforms joint TX/RX optimization due to a more favorable statistic of the scalar weightings of the diagonalized MIMO channel, compared to the joint TX/RX case.

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