MULTIUSER SCHEDULING WITH MATRIX MODULATION

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ABSTRACT

Modern wireless systems enable multiuser scheduling via channel quality feedback. While these systems apply modulation and coding optimized for a SISO channel, in this paper we consider the multiuser scheduling problem in a matrix modulated MIMO channel. It is shown that in a MIMO channel appreciable scheduling gains can be achieved only if the channel quality measurement reflects also the inter-stream interference induced by matrix modulation. Moreover, it is seen that multiuser diversity paves the way for low-complexity receivers in matrix modulated MIMO channels.

1. INTRODUCTION

Single-stream adaptive modulation and coding (AMC) and multiuser scheduling are adopted in modern wireless systems such as HSDPA (3GPP) and 1xEV-DV (3GPP2). In these systems the transmission parameters are selected based on various channel-related measurements. These measurements may include e.g. channel power or channel signal-to-interference ratio. Future wireless systems may support spectrally efficient transmission methods where multiple signal streams are transmitted over a multiple-input multiple-output(MIMO) channel. High symbol rate matrix modulation [3] has been found to perform well in a single-user point-to-point communication links. Therefore, it is of interest to see how to combine multiuser diversity gains and the gains provided by matrix modulation.

In a SISO channel, channel quality indicator (CQI) is determined essentially as a function of the channel signal-to-interference ratio. In a MIMO channel with spatial multiplexing (SM) this does not generally suffice [1]. With spatial multiplexing CQI evaluation should reflect also the inter-stream interference, which with SM depends only on the channel matrix. However, with matrix modulation self-interference is more structured, and this needs to accounted for when designing scheduling metric or CQI. This paper addresses scheduling metrics for matrix modulation via the use of an equivalent channel model. It is shown that relevant gains may be reached with proper scheduling metrics. In addition to performance gains, a conscious design induces also implementation advantages. Indeed, a well-designed multiuser diversity metric simplifies the detection problem. Consequently, a simple linear receiver may suffice.

The paper is structured as follows. Section 2 contains the signal model, accompanied by a characteristic set of high-rate matrix modulators. Section 3 discusses different performance measures, based on equivalent signal models developed for matrix modulators. Section 4 evaluates performance in a multi-user multi-antenna diversity scenario and Section 5 concludes.

2. MIMO CHANNEL AND MATRIX MODULATION

2.1. Signal model

The standard signal model considered here is given by [3]

$$\underset{T\times N_\mathrm{r}}{\mathbf{Y}} = \underset{T\times N_\mathrm{b}}{\mathbf{X}} \underset{N_\mathrm{b}\times N_\mathrm{t}}{\mathbf{W}} \underset{N_\mathrm{t}\times N_\mathrm{r}}{\mathbf{H}} + \underset{T\times N_\mathrm{r}}{\text{noise}} \qquad (1)$$

Above, N_r designates the number of receive antennas, $\mathbf{Y}$ is a $T \times N_\mathrm{r}$ received signal matrix, $\mathbf{X}$ is a $T \times N_\mathrm{b}$ modulation matrix and $\mathbf{W}$ is a $N_\mathrm{b} \times N_\mathrm{t}$ beam-forming matrix. The columns of the channel matrix $\mathbf{H}$ designate channel vectors from N_t transmit antennas to different receive antennas,

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} & \dots & h_{1N_\mathrm{r}} \\ h_{21} & h_{22} & \dots & h_{2N_\mathrm{r}} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_\mathrm{t}1} & h_{N_\mathrm{t}2} & \dots & h_{N_\mathrm{t}N_\mathrm{r}} \end{bmatrix}. \qquad (2)$$

In vector modulation $\mathbf{X}$ is an N_b-vector ($N_\mathrm{b} > 1$), while in matrix modulation $N_\mathrm{b} > 1, T > 1$.

2.2. Modulation matrices

2.2.1. Unconstrained transmission

Parallel or unconstrained transmission across several transmit antennas, according to VBLAST or Spatial Multiplexing, uses a transmission vector

$$\mathbf{X} = [x_1 \ \cdots \ x_{N_\mathrm{t}}], \qquad (3)$$

where $x_1, ..., x_{N_\mathrm{t}}$ are scalar-modulated symbols (e.g. QAM) and each column is associated with a different transmit antenna. The inter-stream interference is dictated by the channel matrix $\mathbf{H}$. Clearly, unconstrained signaling does not provide any transmit diversity gain. Multiple receive antennas are required in decoupling the parallel streams.

2.2.2. Double STTD

Double STTD (DSTTD) [4] adopts two STTD codes, which are transmitted in parallel using four transmit antennas. The code matrix assumes the form

$$\mathbf{X}(x_1, ..., x_4) = \left[\begin{array}{cc} \mathbf{X}(x_1, x_2) & \mathbf{X}(x_3, x_4) \end{array} \right]. \quad (4)$$

2.2.3. Double ABBA

Double ABBA (DABBA) makes a conscious tradeoff between diversity order and code rate. DABBA exploits a transmitter with N_t transmit antennas and (complex) space-time block codes $\mathbf{X}_A, \mathbf{X}_B, \mathbf{X}_C, \mathbf{X}_D$, each with dimension $\mathbb{C}^{N_\mathrm{t}/2 \times N_\mathrm{t}/2}$. The symbols within these matrices are pre-coded by matrix $\mathbf{U}$, a unitary (precoding) matrix. We parameterize the precoding matrix as

$$\mathbf{U}(\mu, \nu) = \left[\begin{array}{cc} \mu & \nu \\ -\nu^* & \mu^* \end{array} \right] \otimes \mathbf{I}_{N_\mathrm{t}/2}. \quad (5)$$

Consider one (quasi-orthogonal) layer involving matrices $\mathbf{X}_A, \mathbf{X}_B$. The precoding matrix is used to rotate the complex symbols $x_1, .., x_{N_\mathrm{t}}$:

$$(y_1, ..., y_{N_\mathrm{t}}) = (x_1, ..., x_{N_\mathrm{t}})\mathbf{U}^T(\mu, \nu), \quad (6)$$

and the rotated symbols are distributed to the two constituent codes:

$$\begin{array}{rcl} \tilde{\mathbf{X}}_A & = & \mathbf{X}_A(y_1, ..., y_{N_\mathrm{t}/2}) \\ \tilde{\mathbf{X}}_B & = & \mathbf{X}_B(y_{N_\mathrm{t}/2+1}, ..., y_{N_\mathrm{t}}) \end{array}. \quad (7)$$

Similarly for the second layer, for (possibly scalar-rotated) symbols $x_{N_\mathrm{t}+1}, ..., x_{2N_\mathrm{t}}$. Thus, transmission matrix is given by

$$\mathbf{X}_{ABCD} = \left[\begin{array}{cc} \tilde{\mathbf{X}}_A & \tilde{\mathbf{X}}_C \\ \tilde{\mathbf{X}}_D & \tilde{\mathbf{X}}_B \end{array} \right]. \quad (8)$$

3. MULTIUSER SCHEDULING AND THE EQUIVALENT SIGNAL MODEL

For resource allocation and scheduling purposes the transmitter is provided with means to rank transmission resources[1]. The relevant information resides typically at the receiver, as opposed to the transmitter, and therefore needs to be signalled to the corresponding transmitting unit. In the considered multiuser system, each receiver is assumed to know the MIMO channel matrix $\mathbf{H}$, e.g. using the common or dedicated pilot channels. Furthermore, each receiver naturally knows the coding and modulation options. These are used to derive a performance measure for matrix modulated transmission below.

[1]The resources may include selection or computation of transmit and reception beams/antennas. For simplicity, it is assumed here that the transmit and receive beams are fixed, e.g. $\mathbf{W} = \mathbf{I}$

3.1. Equivalent channel model

A linear model between the transmitted symbol vector and the received signal needs to constructed separately for different modulation matrices. In this linear model, the channel matrix $\mathbf{H}$ is replaced by an equivalent channel matrix $\mathcal{H}$, which inherits the structure of the modulation matrix, or corresponding the basis matrices [3]. Below, we consider the equivalent channel matrix for one layer of the DABBA matrix described above.

Within one DABBA layer parameters μ and ν within the precoding matrix affect the correlation structure and the equivalent signal model. This can be seen by writing the signal model using the effective channel matrix as

$$\tilde{\mathbf{y}} = \mathcal{H}\mathbf{U}\mathbf{x} + \mathbf{n},$$

where $\tilde{\mathbf{y}}$ is obtained from $\mathbf{y}$ using complex conjugations and linear transformations. After matched filtering with $\mathbf{U}^\dagger \mathcal{H}^\dagger$ a model

$$\mathbf{z} = \mathbf{U}^\dagger \mathcal{H}^\dagger \tilde{\mathbf{y}}$$

arises. With N_r receive antennas and orthogonal constituent codes $\mathbf{X}_A, \mathbf{X}_B$, the receiver decision statistics for the transmitted symbols $\mathbf{x}$ (after matched filtering and signal combining) are

$$\mathbf{U}^\dagger \mathcal{H}^\dagger \mathcal{H} \mathbf{U} = \mathcal{D}_\mathbf{h} + \mathcal{S}_\mathbf{h}, \quad (9)$$

where

$$\mathcal{D}_\mathbf{h} = \left[\begin{array}{cc} a_1 & 0 \\ 0 & a_2 \end{array} \right] \otimes \mathbf{I}_{N_\mathrm{t}/2}, \quad (10)$$

and

$$\mathcal{S}_\mathbf{h} = \left[\begin{array}{cc} 0 & b \\ b* & 0 \end{array} \right] \otimes \mathbf{I}_{N_\mathrm{t}/2}, \quad (11)$$

and where

$$\begin{array}{rcl} a_1 & = & p_1|\mu|^2 + p_2|\nu|^2 \quad (12) \\ a_2 & = & p_2|\mu|^2 + p_1|\nu|^2 \quad (13) \\ b & = & (p_2 - p_1)\mu^*\nu \quad (14) \\ p_1 & = & \sum_{j=1}^{N_\mathrm{r}} \sum_{i=1}^{N_\mathrm{t}/2} |h_{i,j}|^2 \quad (15) \\ p_2 & = & \sum_{j=1}^{N_\mathrm{r}} \sum_{i=N_\mathrm{t}/2+1}^{N_\mathrm{t}} |h_{i,j}|^2. \quad (16) \end{array}$$

Design criteria and designs for determining optimal μ and ν were derived in [3]. These designs are beyond the scope of this paper. However, one should notice that the equivalent channel model, or the equivalent channel correlation matrix, depends on both the channel realizations and the precoding matrix. Furthermore, since different users have different channels, the multiuser system has a collection of signal models. The system should select the model that yields highest performance.

3.2. Performance measures

In the absence of interference one may compute the Frobenius norm of the channel matrix, to determine the received signal power. With non-orthogonal modulation this is not sufficient, and a more accurate model, using the equivalent channel model, is needed. The system can then compute appropriate performance measures, such as signal-to-noise-interference (SINR), bit/packet error probability approximations, capacity estimates, throughput estimates etc. for each hypothetized non-orthogonal matrix modulation method.

Closed-form performance approximations are computationally attractive and consequently preferred herein. These may be tailored not only for transmission methods alone, but also for the overall transmission-reception chain including the receiver resources. As an example, if the receiver houses a linear MMSE detector we may compute filtering matrix

$$\mathbf{L} = (\mathcal{H}^{\dagger}\mathcal{H} + \sigma^2\mathbf{I})^{-1}, \tag{17}$$

where $\mathcal{H}$ is the equivalent channel matrix and σ^2 is the noise power. An approximate BER equation for this receiver, assuming for simplicity a real-valued signal model with BPSK coordinate constellations, assumes the form

$$P_b = \frac{2}{|\{\bar{\mathbf{x}}\}|}\sum_{\bar{\mathbf{x}}} Q\Big(\frac{a_k(\bar{\mathbf{L}}^{\dagger}\bar{\mathcal{R}})_{k,k}(1+\sum_{j\neq k} a_j(\bar{\mathbf{L}}^{\dagger}\bar{\mathcal{R}})_{k,j}\bar{x}_j)}{\sigma\sqrt{(\bar{\mathbf{L}}^{\dagger}\bar{\mathcal{R}}\bar{\mathbf{L}})_{k,k}}}\Big), \tag{18}$$

where $\bar{\mathbf{L}}$ contains the coefficients of linear detector using the real model, Q denotes the complementary error function and the summation spans over 2^{K-1} bit sequences. The transmit amplitude of stream k is denoted by a_k. A simpler performance estimate can be obtained by invoking the Gaussian approximation (see [3] for references) using coefficients

$$\gamma_{k,j} = a_j(\bar{\mathbf{L}}^{\dagger}\bar{\mathcal{R}})_{k,j},$$

$$\beta_k = \frac{a_k(\bar{\mathbf{L}}^{\dagger}\bar{\mathcal{R}})_{k,k}}{\sigma\sqrt{(\bar{\mathbf{L}}^{\dagger}\bar{\mathcal{R}}\bar{\mathbf{L}})_{k,k}}}, \tag{19}$$

and

$$\lambda_k^2 = \frac{\beta_k^2\sum_{j\neq k}\gamma_{k,j}^2}{\gamma_{k,k}}.$$

Using these notations, a computationally attractive and accurate approximation to error probability for the kth stream is given by

$$P_b = Q\Big(\frac{\beta_k}{\sqrt{1+\lambda_k^2}}\Big). \tag{20}$$

The fraction $\gamma_{k,j}/\gamma_{k,k}$ quantifies interference leakage between the kth and jth stream. This vanishes for the decorrelating detector, $\lambda_k^2 = 0, \forall k$. This BER measure can be further decomposed into BER measures for different substreams. This is useful when the substreams are coded and/or modulated using different techniques. It is clear that a number of performance or capacity estimates may be devised. However, for the present discussion, it is only important that these estimates are based on an equivalent channel model that reflects the inter-stream interference between different streams in a given matrix modulation method.

With decorrelating performance metric it sufficient to calculate only β_k (or e.g. the average of $\{\beta_k\}$) for each user, based on their respective equivalent signal models. Denote the mth user's scalar performance measure by κ_m in the following. Each κ_m is quantized, and sent to the transmitter using a feedback channel. The transmitter (e.g. base station) the selects the user m^* (of max M users) with index

$$m^* = \arg_m \max\{\kappa_1, ..., \kappa_M\}. \tag{21}$$

In many cases user selection based on β is only a crude approximation to achievable performance, and more accurate scheduling metrics may be devised, based on the equivalent channel model. However, it nevertheless reflects the effect of the received channel, the matrix modulation format, and the induced inter-stream interference in a concise formula. Including these factors into the performance estimate is crucial, as will be seen below.

4. PERFORMANCE

In the following example we provide some numerical examples of possible gains when multiuser scheduling and matrix modulation are combined. In the considered case we have 1,2,4,8, or 16 users, each with identical channel statistics. The users evaluate either their κ_m when SINR-based scheduling is used, or alternatively the received signal power as determined by the Frobenius norm of the channel matrix. In both cases the respective performance measures (e.g. κ_m) are signalled to the transmitter, which selects the user. This user is allocated fixed (full) transmit power while all other users are silent.

Consider both coded and uncoded performance. In figures E_b specifies the total transmitted signal power per bit, and No designates noise power per one receiver antenna. With channel coding, the bits within the QPSK symbols in DABBA matrix are subjected to rate 4/5 Turbo coding with frame size 378 bits. The spectral efficiency is thus 3.2 bps/Hz. Each user has identical channel statistics and an aggregate performance measure averaged BER over all users is used. Results are shown in Fig. 1 for both Frobenius-based and SINR-based scheduling. In figures E_b specifies the total transmitted signal power per bit, and No designates noise power per each receiver antenna. The figure demonstrates that Frobenius norm is not a sufficiently accurate performance measure. Proper multiuser diversity gains can only be obtained by using a more accurate measure. Here,

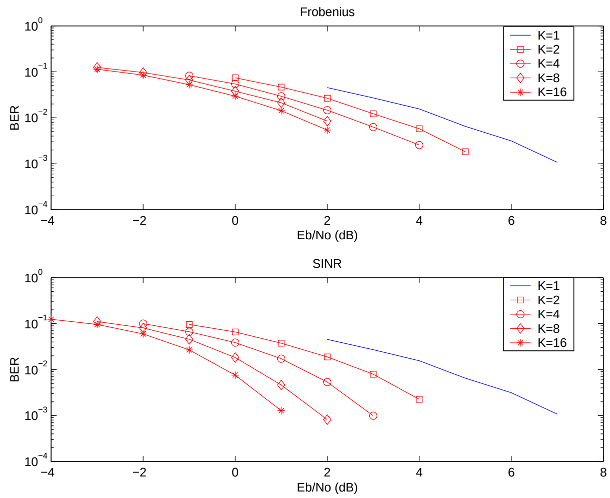

Figure 1: Performance with Frobenius and SINR-based multiuser scheduling. Coded BER averaged over M users.

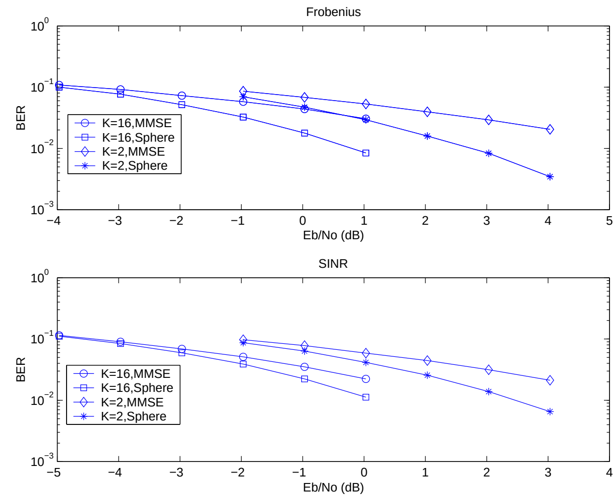

Figure 2: Uncoded BER with Frobenius and SINR-based multiuser scheduling with MMSE detection or Sphere decoding.

the decorrelating measure β yields several dB gain when the number of users is high.

Fig. 2 depicts the uncoded bit-error-rate in two separate cases, involving two and sixteen users. Again, either Frobenius norm-based scheduling or SINR-based scheduling is used. With SINR-based scheduling the scheduled user tends to have a favorable equivalent channel matrix and therefore even a low-complexity MMSE detector provides satisfactory performance. This suggests that (with properly selected scheduling criteria) system level MIMO gains may be high even in the absence of optimal (maximum likelihood) detection.

5. CONCLUSION

This paper has quantified the achievable multiuser scheduling gains in a MIMO channel using non-orthogonal matrix modulation. It was shown that appreciable scheduling gains are obtained provided that the scheduling metrics are sufficiently accurate. Here, measures based on the equivalent channel matrix clearly outperformed simpler measures that are based only on channel power. With an appropriate scheduling metric the performance difference between a single user system and a multiuser system is several decibels (e.g. 2-7 dB depending on operation point and the number of users). Interestingly, multiuser diversity also eases the detection problem for the scheduled user. Thus, a relatively simple (linear) receiver may suffice in a multiuser scenario.

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6. REFERENCES

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