Linear Dispersion Codes Selection Using WiMAX over Uncorrelated MIMO Rayleigh Channel

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Abstract. In this paper the combination of Transmit Antenna Selection with Linear Dispersion Code Selection is proposed and analysed. The bit error rate metric criterion is proposed (bit error rate minimization and throughput maximization) to evaluate the performances. The performance of the proposed spatial link adaptation scheme is evaluated under low mobility environment and MIMO uncorrelated Rayleigh channel. Concluded analysis shown that maximum spatial diversity is achieved as well as a smooth transition between codes with low spatial multiplexing rate and high spatial diversity (suitable for low SNR), and codes with high multiplexing rate but low diversity order (suitable for high SNR) in order to maximize the overall system throughput[1].

Keywords: MIMO, Spatial link adaptation, Transmit Antenna Selection, Linear Dispersion Codes, WiMAX.

1 Introduction

Analogously to channel coding in SISO links, two types of channel coding have been used for MIMO channels: block coding (referred as Space Time/Frequency Block Coding, STBC/SFBC) and convolutional coding (referred as Space Time Trellis Coding, STTC) [1][2]. For the STBC case, the codeword is only a function of the input bits, whereas the encoder output for the STTC is a function of the input bits and the encoder state (which depend on previously transmitted bits). Both STBC and SFBC codes are very similar, in STBC the coding is performed along the space and time dimension where the channel must remain static during a certain period larger than the codeword (valid for low mobility environments) duration. Whereas in SFBC codes the coding is performed along the space and frequency domains where the

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codeword spanning must be less than the coherence bandwidth (hence is valid for environments with low delay spread). Since the channel is assumed constant in both previous coding procedures for the whole codeword, thus, the analysis of STBC is also valid for SFBC and the same conclusions can be drawn for both.

The inherent memory of the STTC provides an additional coding gain compared to the STBC at the expense of higher computational complexity [5][4][6]. However, since STBC transforms the MIMO channel into an equivalent scalar additive white Gaussian noise (AWGN) channel [3], the concatenation of traditional convolutional (or Trellis) coding with STBC outperforms the STTC with low number of receive antennas ($M,N\leq 2$) [5] and same number of encoder states. Moreover, for a higher number of transmit and receive antennas, the STBC codes designed under the Linear Dispersion Codes (LDC) framework (which are able to preserve channel capacity) combined with convolutional codes are also preferred, since they achieve similar performance at lower computational cost compared with STTC codes with a high number of Trellis states [11].

Therefore, due to the higher flexibility of the LDC (i.e. linear STBC) codes, in order to adjust the diversity-multiplexing tradeoff as well as their low complexity, the authors focused on this class of space-time coding for the subsequent analyses [12].

In this paper, we investigated different spatial adaption and precoding mechanisms that can be used in combination with the adaptation mechanism in uncorrelated Rayleigh MIMO channel. A new spatial adaptation algorithm called "*Transmit Antenna and space-time Coding Selection*" (TACS) is introduced and evaluated. This new scheme combines the well-known transmit antenna selection techniques with the precoding schemes where the transmitter selects the best space-time codes according to the channel state information changes.

The rest of the paper is organized as the following: in Section 2, the system model considered is introduced. The proposed TACS's selections criteria are detailed in Section 3, and the corresponding simulation results are analyzed in Section 4. Finally, conclusions are stated in Section 5, where the performance behaviours of the proposed approach are summarized.

2 Proposed Transmit Antenans and Code Selection (TACS)

When partial CSIs information is available at the transmitter two common selection techniques could be applied which are: the space-time code selection, and the transmit antenna selection. One of the first works joining both concepts is that presented by Heath *et al.* in [7]where the number of the spatial streams (in the SM case) are adapted by selecting the best set of transmitter antennas (i.e. $M=M_a$).

Then, given an antenna subset and a fixed rate, the required constellation could be determined as well as the number of spatial streams. A simplification of this optimization problem is given in [7][8] where each stream is switched on/off when the post-processing of the SNR value of the stream is above/below a fixed threshold which is related with the rate. Further extensions of space-time code selection with transmit antenna selection are given by Machado et al. in [8] where the available codes in the codebook are; the Alamouti code, the SM with M=2, the Quasi-OSTBC with M=3 and single antenna transmission.

In addition, the space-time code selection with transmit antenna selection has been generalized by the author in [9][10] under the LDC framework. This generalization allowed us to use any type of linear STBC (independently of the optimization criteria) and determine which codes are used most times and under which channel conditions. In the following subsections, the spatial adaptation schemes based on transmit antenna selection and LDC selection (referred as Transmit Antenna and Code Selection – TACS) is evaluated, where the performance results obtained through computer simulations are analyzed in section 6.

3 System Model

The MIMO system model with M and N transmitter and receiver active antennas respectively is considered and defined by

$$\mathbf{Y} = \sqrt{\frac{\rho}{M}}\mathbf{HS} + \mathbf{N}, \tag{1}$$

where $\mathbf{S} \in \mathbb{C}^{M\times T}$ and $\mathbf{Y} \in \mathbb{C}^{N\times T}$ are the transmitted and the received signals from each antenna during each channel access, and the channel matrix $\mathbf{H} \in \mathbb{C}^{N\times M}$ is assumed constant during T periods (i.e. block fading channel model). The transmitted signal has unitary power, and the noise matrix $\mathbf{N}$ follows a circular complex Gaussian distribution with zero mean and unitary standard deviation. The Linear Dispersion Code (LDC) structure subsumes most of the Space-Time (ST) codes such as the Bell-Labs Layered Architecture Space Time coding (BLAST), the Alamouti scheme, etc. [6]. Then, considering the LDC framework, the transmit signal matrix $\mathbf{X}$ has necessarily the following structure

$$\mathbf{S} = \sum_{q=1}^{Q}\left(\alpha_q \mathbf{A}_q + j\beta_q \mathbf{B}_q\right), \tag{2}$$

where $\mathbf{A}$, $\mathbf{B} \in \mathbb{C}^{M\times T}$ are the basis matrices, $\mathrm{E}\{\mathrm{tr}(\mathbf{S}^H\mathbf{S})\}=MT$, and the values $s_q = \alpha_q + j\beta_q$ are the complex data symbols , the transmit power is unitary $\mathrm{E}\{s_q^* s_q\}=1$. The number of basis matrices is Q, and the spatial multiplexing rate is Q/MT. The rate R achieved by the system is given by $R=Qn/T$ [bits/s/Hz], where n means the number of bits transmitted per each complex symbol.

Then, substituting (2) into (1) and applying the *vec* operator on both sides of the expression, the (real valued) system equation can be rewritten as

$$\begin{bmatrix} \Re(\mathbf{y}_0) \\ \Im(\mathbf{y}_0) \\ \vdots \\ \Re(\mathbf{y}_{Q-1}) \\ \Im(\mathbf{y}_{Q-1}) \end{bmatrix} = \sqrt{\frac{\rho}{M}}\mathcal{H}\begin{bmatrix} \alpha_0 \\ \beta_0 \\ \vdots \\ \alpha_{Q-1} \\ \beta_{Q-1} \end{bmatrix} + \begin{bmatrix} \mathbf{n}_0 \\ \mathbf{n}_0 \\ \vdots \\ \mathbf{n}_{Q-1} \\ \mathbf{n}_{Q-1} \end{bmatrix} \tag{3}$$

where **s** is the real input symbols vector, and **n** is the real vector noise i.i.d. components $\mathcal{N}(0,1/2)$-distributed. The equivalent real valued channel matrix $\mathcal{H} \in \mathbb{R}^{2NT\times 2Q}$ is then given by

$$\mathcal{H} = \underbrace{\left[\mathbf{I}_N \otimes \mathcal{A}_0 \quad \mathbf{I}_N \otimes \mathcal{B}_0 \quad \dots \quad \mathbf{I}_N \otimes \mathcal{A}_{Q-1} \quad \mathbf{I}_N \otimes \mathcal{B}_{Q-1}\right]}_{2NT\times 4MNQ} \times \underbrace{\left[\mathbf{I}_{2Q} \otimes \underline{\hbar}\right]}_{4MNQ\times 2Q}. \tag{4}$$

with

i.
$$\mathcal{A}_q = \begin{bmatrix} \Re\{\mathbf{A}_q\} & -\Im\{\mathbf{A}_q\} \\ \Im\{\mathbf{A}_q\} & \Re\{\mathbf{A}_q\} \end{bmatrix}_{2T\times 2M}, \quad \mathcal{B}_q = \begin{bmatrix} -\Im\{\mathbf{B}_q\} & -\Re\{\mathbf{B}_q\} \\ \Re\{\mathbf{B}_q\} & -\Im\{\mathbf{B}_q\} \end{bmatrix}_{2T\times 2M}, \quad \underline{\hbar} = \begin{bmatrix} \hbar_0 \\ \hbar_1 \\ \vdots \\ \hbar_{N-1} \end{bmatrix}_{2MN}, \; \hbar_n = \begin{bmatrix} \Re\{\mathbf{h}_n\} \\ \Im\{\mathbf{h}_n\} \end{bmatrix}_{2M}, \tag{5}$$

where $\mathbf{h}_n$ is the n-th row of the MIMO channel matrix $\mathbf{H}$.

Typically, the maximum likelihood (ML) detection is assumed during the LDCs design. However, it is well-known that the complexity requirement derived from such decoding technique is extremely high ($\mathcal{O}(2^{Qn})$), making the ML detector high-priced for high data rates in real implementations. Furthermore, due to the linear relationship between input and output samples observed in (3), a linear detector is enough to recover the symbols. However, the performance of such linear decoder is far from that offered by the ML. Nevertheless, one important benefit from using a linear decoder is that an equivalent channel can be estimated for each symbol, hence adaptive coding and modulation (ACM) can be applied on a per symbol basis. In fact, using a linear minimum mean square error (MMSE) receiver, the Effective Signal to Interference and Noise Ratio (ESINR) per each symbol q is given by

$$ESINR_q^{(MMSE)}(\mathbf{H}) = \frac{\rho}{M\left[\mathbf{H}^H\mathbf{H} + 2\rho^{-1}\mathbf{I}_{2Q}\right]^{-1}_{q,q}} - 1, \tag{6}$$

where $\mathbf{X}^{-1}_{q,q}$ refers to the (q,q) element from $\mathbf{X}^{-1}$, and $\rho=P_{rx}/N_0$ is the average signal to noise ratio (SNR), P_{rx} here is the received power. Furthermore, if the mapping applied on the symbols follow a 2^n-QAM constellation the average pair wise error probability per stream by applying the Nearest Neighbour Union Bound can be given by

$$P_{e,q} \leq 1 - \left(1 - N_e(n) \cdot \mathrm{E}\left\{ \mathbf{Q}\left(\sqrt{ESINR_q(\mathbf{H}) \frac{d_{\min}^2(n)}{2}} \right) \right\} \right) \quad (7)$$

where $Q(x)=0.5\times erfc(x/2^{1/2})$, d^2_{min} is the squared minimum distance between any two points of the constellation (assuming an unitary average transmission power), and N_e is the average number of nearest neighbours constellation points. For a 2^n-QAM modulation $d_{min}^2=6/(2^n -1)$ and $N_e = 4\times(1-2^{-n/2})$. In addition, in case all the symbols within the codeword apply the same modulation, the average pair wise error probability for the whole codeword is usually approximated and given by (assuming $P_e<10^{-2}$)

$$P_e \leq Q \cdot N_e(n) \cdot \mathrm{E}\left\{ \mathbf{Q}\left(\sqrt{ESINR_{\min}(\mathbf{H}) \frac{d_{\min}^2(n)}{2}} \right) \right\}, \quad (8)$$

where $ESINR_{min}=min(ESINR_0,\ldots, ESINR_{Q-1})$ [15]. Nevertheless, assuming that ML is feasible at the receiver side, the authors propose the following expression

$$ESINR_q^{(ML)} \approx \frac{P_{rx} \cdot \left\|\mathbf{H}_q\right\|_F^2 \cdot T/MQ'}{K_n N_0 + K_i \cdot P_{rx} \cdot \left\|\mathbf{H}_q\right\|_F^2 \cdot T/MQ'}, \quad (9)$$

to model the Effective Signal to Interference and Noise Ratio (*ESINR*) per transmitted symbol q when the ML detector is used. $\|H_q\|_F^2$ is the Froebenius norm of the channel matrix obtained considering only the transmitting antennas. Q' means the number of streams transmitted per antenna, K_n and K_i are the noise and interference weighting terms respectively what depend on the modulation order as well as the LDC code used (see Table 1). The values shown in Table I have been obtained by computer simulation for the Alamouti code, the SM and the Golden code, in case of BPSK, QPSK and 16QAM modulations when M/N/T=2/2/2.

Table 1. Values of K_n and K_i for linear STBC when $M/N/T$ = 2/2/2

Modulation	***LDC_{SIMO}(R=1)***		***$LDC_{Alamouti}$(R=1)***		***LDC_{SM}(R=2)***		***LDC_{Golden}(R=4)***	
	K_n	K_i	K_n	K_i	K_n	K_i	K_n	K_i
BPSK	1	0	1	0	0.9	0.111	1	0.066
QPSK	1	0	1	0	1	0.071	1.6	0.035
16QAM	1	0	1	0	1.9	0.013	2.5	0.010

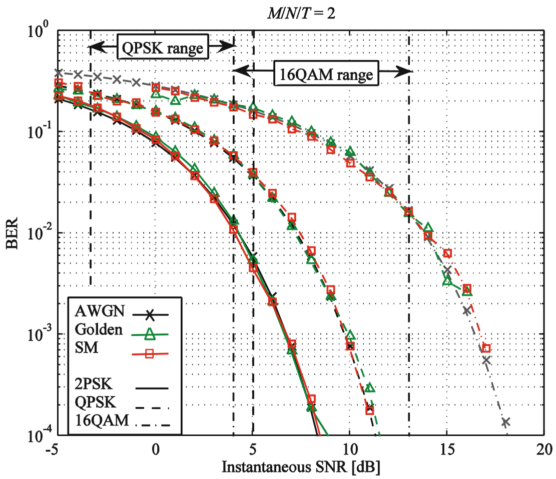

Fig. 1. BER performances when N=2, R=4, M_a={2,3,4} for uncorrelated MIMO Rayleigh channel and MMSE linear receiver

The evaluation of this model has been carried out by link level simulation comparing the measured bit error rate with those obtained assuming the *ESINR* in Eq. (9), and the theoretical BER expression for an AWGN channel. Only the performance of the Spatial Multiplexing (SM) and Golden code are illustrated (for SIMO and Alamouti since there is no interference so the justification is straightforward). It can be observed in Figure 1, that within the SNR range where the modulations are relevant (e.g. uncoded BER $\leq 10^{-4}$), the bit error rate curves match the theoretical AWGN performance very tightly. The main advantage of the ESINR equation approximation in (9) is that its easily estimates the optimum modulation and coding scheme (MCS) according to instantaneous channel conditions on a per stream (i.e. symbol) basis. Notice that for LDC code as the Spatial Multiplexing, the ESINR per stream is perfectly modelled obtaining different ESINRs for each of the streams.

4 STC Selection Performances under Bit Error Rate Minimization Criterion

Then, given the ESNR per stream in (6), and the average pair wise error probabilities in (7) and (8), two different optimization scenarios are studied where both the transmit antenna subset as well as the best LDC from a set of codes are selected (see Figure 2).

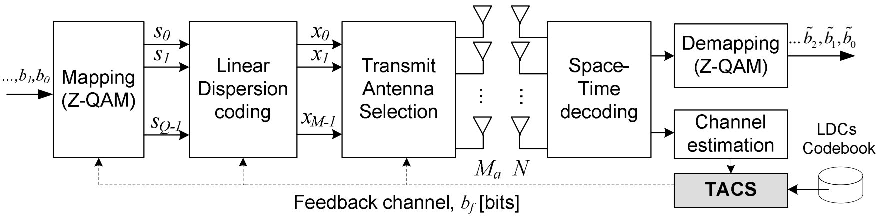

Fig. 2. TACS spatial adaptation scheme and integration into the transmission scheme

In the first scenario, we consider that the same modulation is applied to all the symbols and that the rate R is fixed. In that case, and since the transmission power is fixed, we are interested in selecting the transmitting antenna subset and the LDC codes that minimize the error rate probability (i.e. the bit error rate – BER) while the modulation required by each LDC is adapted in order to achieve the targeted rate R. Since the Q-function is monotonically decreasing as a well as the function of the input, the optimization problem can be defined as

$$\max_{LDC_i, p_i} \min_{q} \left\{ ESINR_q \left(H, LDC_i, p_i \right) d_{\min}^2 \left(n_i \right) \right\}, \tag{10}$$

where i means the LDC index and p_i the transmitting antenna subset (set of antennas that can be used according to the number of transmitter antennas M_a, and the number of antennas required by the LDC). It is also noted that the constellation is a function of the LDC.

In the second scenario, the optimization is performed in order to maximize the system throughput considering a certain quality of service requirement (i.e. a maximum Block Error Rate - BLER). In that case, the problem is formulated as follows

$$\max_{LDC_i, p_i, MCS_j} \min_{q} R\left(1 - BLER\left(ESINR_q\right)\right) \quad \text{s.t.: } BLER \leq \mu \tag{11}$$

where j means the modulation and coding scheme (MCS) index that maximizes the spectral efficiency for the specific channel state subject to a maximum block error rate (BLER). The selection of the optimum MCS is carried out assuming that the ESNR is the SNR that would be obtained at the receiver in case having an (AWGN channel. Under that assumption, there is a direct mapping between each MCS and the obtained BLER for each ESNR value.

5 Performance Analyses

WiMAX time division duplex (TDD) system has been used [16]. The numbers of available transmitter antennas are M_a={2,3,4} whereas the number of receiver antennas is fixed to N=2. One user is simulated which has allocated one subchannel per frame. The channel follows a spatial uncorrelated Rayleigh distribution, whereas a block fading model is assumed per subchannel (flat in frequency and constant in time). It is assumed that the channel is perfectly known at both transmitter and receiver sides.

The basic set of LDC codes that we used for the study are: the *Single Input Multiple Output* code using a Maximum Ratio Combiner (MRC), the *Alamouti* code (referred as G2 in the plots), the *BLAST*-like codes with M=2 (referred as Spatial Multiplexing, SM, in the plots) and the *Golden* code. The codeword length for all the codes is T=2. Moreover, for the SM case two types of encoding have been tested named vertical encoding (SM-VE) and horizontal encoding (SM-HE). For the vertical encoding, the same MCS is used for all the symbols transmitted within the same codeword, whereas for horizontal encoding each data stream (symbol) may apply a different MCS according to the channel status. Actually, all these codes are part of the standard and can be found in [16]. Consequently, since each i-th LDC from this basic set require at most two transmitting antennas, in case $M_i<M_a$ the best set p of transmitting antennas is selected from the M_a available antennas, and since the order in which the antennas are chosen is relevant we have P_i possible transmitting antennas combinations with

$$P_i = C\binom{M_a}{M_i} = \frac{M_a!}{M_i!(M_a - M_i)!}. \tag{12}$$

To solve (10) or (11), an exhaustive search is performed among all the available LDC codes and P antenna sets, despite, it would be very interesting to test the performance of the TACS under an incremented or decremented search as that proposed in [14].

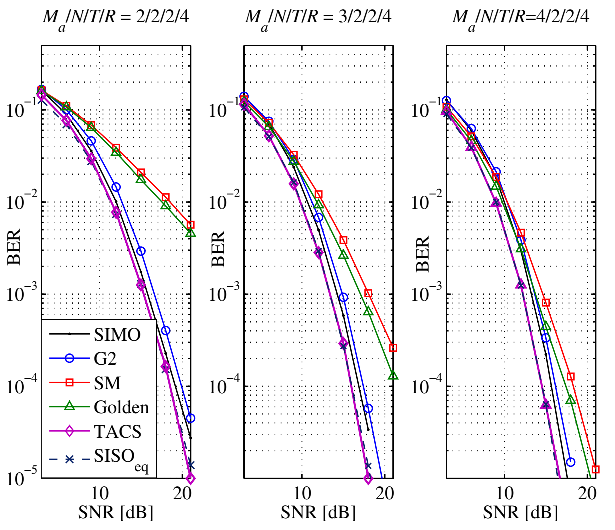

Fig. 3. BER performance when N=2, R=4, M_a={2,3,4} for uncorrelated MIMO Rayleigh channel and MMSE linear receiver

In Figure 3 and Figure 4, the bit error rate performance with the TACS algorithm having a fixed rate R=4. Figure 3 shows the improvement due to the increase in M_a and also the performance achieved when combined with code selection. It can be observed how the TAS increases the diversity order, leading to a large performance increase for the SM and Golden subsets. It is very important to notice that despite the diversity increase for all the LDC subsets, the Alamouti's Spatial Diversity (SD) and SIMO schemes still perform better when each code is evaluated independently. However, in Figure 4 , we can observe that when the code selection is switched on, SIMO and Golden subsets are selected most times, while the usage of SIMO increases with the SNR and the usage of SM and the Golden code stay low and constant with M_a.

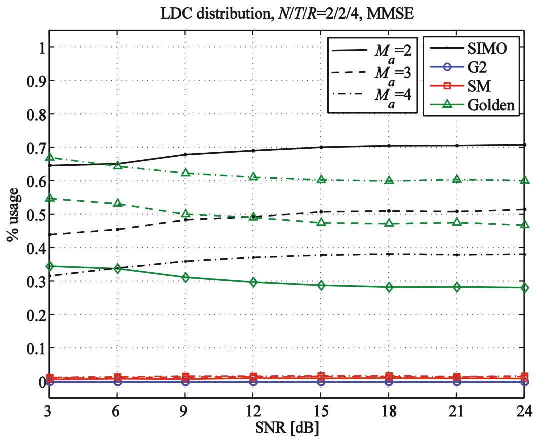

Fig. 4. LCD selection statistics when N=2, R=4, M_a={2,3,4}, for uncorrelated MIMO Rayleigh channel and MMSE linear receiver

In Figure 5, the linear MMSE and ML detectors performances are compared. Since the ML achieves higher diversity order than the MMSE detector, the performance is clearly superior. However, the computational complexity of the ML is exponential with R (and T). As a result, for data rates R>4 it is unfeasible to implement ML in a practical system. It is also observed that the Golden code and the SM are the most benefited from the ML detector since the diversity order is increased, leading to lower BER. In case of ML decoding, the superiority in performance of the Golden code w.r.t. SM is evident. When comparing the Golden code and SD, it is observed that for data rates R≥4 the Golden code outperforms SD. This can be attributed to the fact that in case R=4 the modulation used with the Golden code is a 16QAM whereas for SD a 256QAM is required. So, although the SNR for each stream is higher with the SD, the BER is increased due to the higher order modulation.

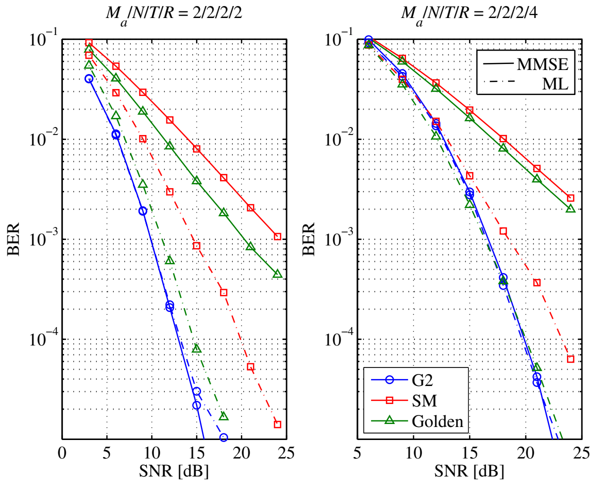

Fig. 5. BER performance with M_a=2, N=2, R={2,4} and uncorrelated MIMO Rayleigh channel, for MMSE and ML detectors

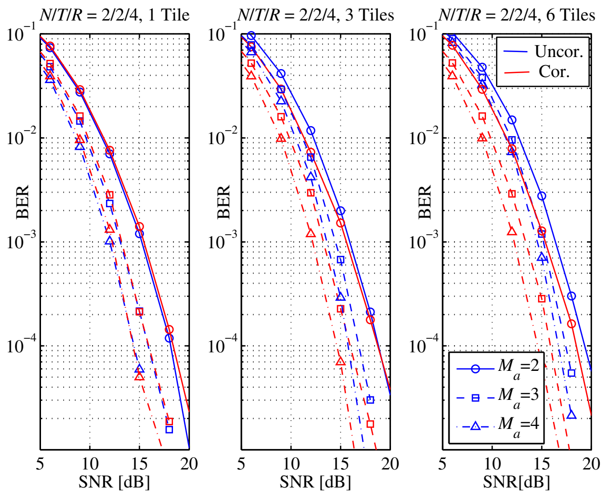

Fig. 6. Effects of optimization over broadband MIMO channels (MMSE detector)

In Figure 6 and Figure 7 the effects of optimizing over a larger number of tiles is investigated. Using an MMSE linear receiver, it can be appreciated in Figure 6 that the TACS scheme performs better in case of correlated channels, something obvious since it is based on a "*max-min*" cost function and as the degrees of freedom in the optimization set are increased (i.e. the PUSC scheme with higher number of tiles) the minimum channel value across the set also decreases. The performance difference between the TACS for correlated and uncorrelated channels is between 1dB for M_a=2, and 3dB for M_a=4.

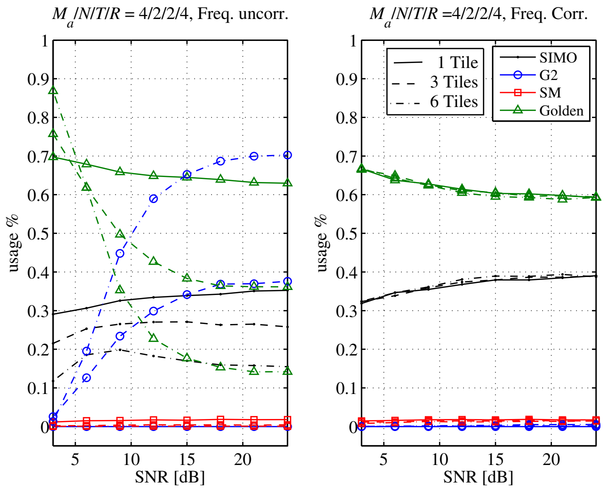

Fig. 7. Usage of the LDC codes when optimizing over broadband MIMO channels

Nevertheless, looking to Figure 7 may clarify the difference in performance for both channels. When we observe the LDC usage distribution in the correlated channel (Figure 7 - right plot), we can conclude that the TACS is not so much affected by the optimization over a larger set of tiles.

However, in case the channel is uncorrelated we can observe how the spatial diversity scheme (G2) becomes the most frequently used LDC code as the number of tiles per subchannel is increased. This result could be also verified, since for uncorrelated channels with a large number of tiles it is not clear that one antenna subset may perform well for all the tiles, so the best choice is to use the scheme with higher native diversity (i.e. higher diversity without transmit antenna selection), and this is the G2. So we can conclude from the above analysis that the TACS proposed scheme is aware of channel correlation inside each tile, and also between tiles, selecting the optimum code accordingly.

6 Conclusions

This paper aims to fill the gap between Transmit Antenna Selection and space-time code selection. The well-defined LDC framework has been used to characterize any linear STBC. The Transmit Antenna and Code Selection (TACS) scheme has been evaluated under bit error rate minimization. We can conclude from the presented performance analysis that the TACS proposed scheme is aware of channel correlation inside each tile, and also between tiles, selecting the optimum code accordingly. It has been also shown that TACS achieves the maximum diversity order as well as a remarkable SNR gain. Then it seems logical to consider the TACS with LDC code selection scheme with linear receivers where computational complexity at the mobile station must be kept as low as possible in order to save the batteries energy.

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