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# Link Adaptation for Spatial Multiplexing MIMO Systems

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*Abstract:* A fast near-optimal transmission scheme selection algorithm for multiple-input multiple-output (MIMO) systems using spatial multiplexing and linear detection is proposed and analyzed. The algorithm selects a transmit antenna subset such that applying available coding and modulation (CM) modes on each spatially multiplexed substream optimises the throughput under constraints on maximum expected bit error rate (BER) assuming straightforward linear detection. Comparing the performance of the system applying proposed and optimal selection algorithms nearly no degradation is observed with the former. The simulation results also show that a low-rate feedback specifying the active antennas and CM mode per each active antenna enables high spectral efficiency and reliability even for straightforward linear detection.

*Key-Words:* MIMO systems, spatial multiplexing, antenna selection, adaptive modulation, multimode selection

## 1. Introduction

Wireless communication systems with multiple antennas at both ends, known as multiple-input multiple-output (MIMO) systems, were proved to be able to achieve very high spectral efficiencies [1]. The most straightforward approach to benefit from the MIMO wireless channel is spatial multiplexing, where the data is divided into multiple substreams and each substream is transmitted on a different transmit antenna [2]. A range of methods including linear, iterative and maximum likelihood (ML) decoding can be used to decode the transmitted substreams.

Linear receivers are important due to their low complexity, but they incur a loss of diversity advantage relative to the ML receivers [3]. Performance of linear receivers is even worse in correlated channels, since they are based on matrix inversion, which can be ill-conditioned and increases noise at the detection. However, it has been proved that using a low-rate feedback channel improves the performances of low complexity MIMO systems substantially [3-5].

In our system both the number of substreams transmitted and the subset of active transmit antennas are chosen dynamically, based on the received signal using the feedback loop [3]. We have improved the transmit antenna selection algorithm introduced in [6] to take into account also the properties of the available CM modes. The proposed adaptive MIMO system is described in the second section. The new algorithm which determines the set of transmit antennas and selects the mode for each antenna is described next. The performance of the algorithm for QAM modulation is evaluated by computer simulations. We compare this to a number of alternative schemes, namely: optimal transmission scheme selection obtained by exhaustive search; adaptation with orthogonalisation of the subchannels; a system with optimal per-substream CM; and a system without antenna selection. In the conclusion some remarks are given and further work is proposed.

## 2. Adaptive MIMO system

A MIMO system consists of multiple transmit ($M_T$) and multiple receive antennas ($M_R$). In this paper we shall assume a quasistatic and flat fading channel. The received signal on the *j-th* receive antenna is

$$y_j = \sum_{i=1}^{M_T} h_{ij} x_i + n_j , \tag{1}$$

where $x_i$ is the transmitted signal from *i-th* transmit antenna and $y_j$ is the received signal at the *j-th* receive antenna. The variable $n_j$ denotes the sample of the circularly symmetric complex Gaussian noise with variance $\sigma_n^2$ at the *j-th* receiver. The fading channel is described as a sum of complex paths $h_{ij}$ between receive and transmit antennas. In the Rayleigh channel the complex gain coefficient $h_{ij}$ follows the Gaussian distribution. The matrix form of (1) is

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} , \tag{2}$$

where **y** is the column vector of the received signal, **H** is the channel matrix, **x** is the column vector of the transmitted signal and **n** is the column vector of additive white Gaussian noise. Accurate detection of the MIMO signal requires knowledge of the channel state information (CSI) at the receiver.

A block diagram of the proposed adaptive MIMO system is shown in Fig. 1. The data sequence is split by the bit splitter into parallel sub-streams, which are converted into $M_t \leq M_T$ parallel symbols in the symbol mapper, where $M_t$ is the number of spatially multiplexed substreams selected by the transmission scheme selection algorithm described in the next section. Each symbol is then coded with FEC and modulated. The channel mapper directs the baseband signals to the radio frequency (RF) transmitters and switches off those transmitters which are not used. At the receiver the $M_R$ RF down converters transform the signal back to the baseband. The linear MIMO signal detector estimates the transmitted signal using the estimated CSI.

On the receive side the channel estimation block estimates the channel matrix **H** once per burst. The estimated channel matrix **H** is fed into the linear signal detector and optionally into the channel prediction block. A transmission scheme is next selected according to the original or predicted channel matrix. $M_T$ values, $m_1..m_{MT}$, describing the CM mode for each transmit antenna for the next transmission burst, are sent back to the transmitter. If any value is equal to zero, the corresponding antenna is switched off and no data is transmitted using that antenna.

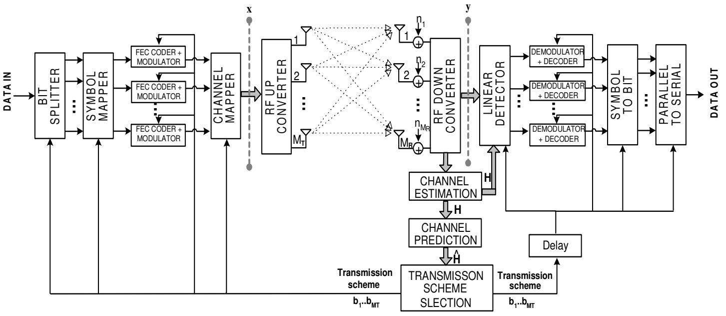

***Figure 1:*** *Block diagram of proposed adaptive MIMO system.*

In this paper we limit our analysis to the transmission scheme selection algorithm described in the next section, since it is the essential part of the adaptive MIMO system. Perfect channel estimation and feedback are assumed.

## 3. Transmission scheme selection

In this section the algorithm which determines the subset of active transmit antennas and selects the CM mode for each antenna is introduced. There are $2^{M_T}$ possible subsets of active transmit antennas, therefore evaluating all the possibilities is usually computationally too complex, especially for higher number of transmit antennas available. The block diagram of the proposed link adaptation algorithm is shown in Fig. 2. The algorithm input is the estimated or predicted channel matrix **H**.

Post-detection signal to noise ratio (SNR), sometimes also called post-processing SNR, can easily be calculated if simple linear ZF detection is presumed [4], [6]. First the Moore-Penrose pseudoinverse of channel matrix **H** is calculated, denoted **G**. Assuming ZF detection, the post-detection SNR of the $i$-th transmit antenna can be expressed:

$$SNR_i^{ZF} = \frac{P_i}{N_0} \frac{1}{\sum_{j=1}^{M_R} \left| g_{ij} \right|^2}, \tag{3}$$

where $P_i$ is the average power of the signal transmitted by $i$-th antenna, $N_0$ is power of white additive noise at each receive antenna, and $g_{ij}$ are the elements of the matrix **G**. The term $(P_i/N_0)$ in (3) depends on the transmitted power at each antenna and the receiver implementation, while the second term depends on the channel characteristics. Equation (3) can be derived by considering the linear detection process where the transmitted data is estimated by multiplying the column vector of the received signals **y** by the equalizer matrix **G**:

$$\hat{\mathbf{x}} = Q(\mathbf{G}\,\mathbf{y}) = Q(\mathbf{G}(\mathbf{H}\mathbf{x} + \mathbf{n})) = Q(\mathbf{x} + \mathbf{G}\,\mathbf{n}), \tag{4}$$

where $Q$ is the demodulation process and $\hat{\mathbf{x}}$ denotes the estimate of the transmitted signal vector **x**. The transmitted signal from the $i$-th transmit antenna is distorted by the additive noise from $M_R$ receive antennas:

$$\hat{x}_i = Q\left(x_i + g_{i1}n_1 + g_{i2}n_2 + \cdots + g_{iM_R}n_{M_R}\right). \tag{5}$$

Similarly the post-detection SNR for the case of linear minimum mean-square error (MMSE) could be estimated [4] and used in the algorithm.

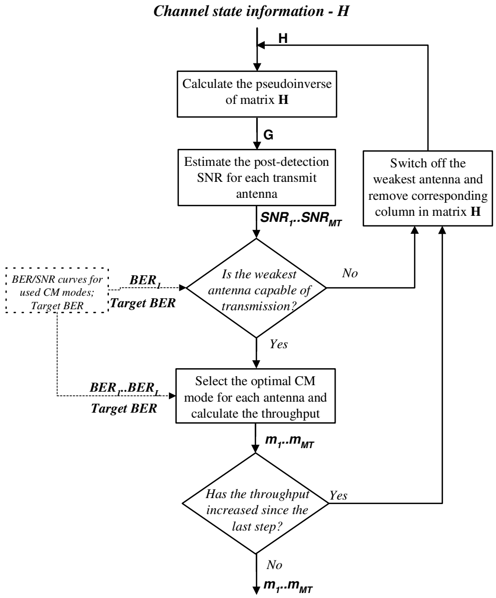

***Figure 2:*** *Block diagram of the algorithm for selecting transmit antennas and their CM modes.*

In the next step the algorithm checks whether the target BER can be achieved on the weakest antenna (the antenna with the lowest $SNR_i^{ZF}$). If the weakest antenna cannot achieve the target BER even with the most robust CM mode, it is switched off and eliminated from the transmission scheme. This changes the channel matrix **H** since the corresponding column is not relevant any more and can be removed from the channel matrix. A new pseudoinverse matrix **G** is calculated from the deflated matrix **H**, giving a new higher post-processing $SNR_i^{ZF}$ for the rest of the spatially multiplexed substreams, since the channel matrix is better conditioned. This step is repeated until all the remaining transmit antennas are capable of sufficiently reliable transmission, the inner loop in Fig. 2.

The inner loop guarantees that the expected BER for each multiplexed substream will not exceed the given target BER. In the outer loop the algorithm attempts to increase the throughput of the system by further decreasing the number of multiplexed substreams, but increasing the amount of information allocated in each substream. This can also be explained as a tradeoff between diversity and multiplexing [3], [8], [9], since reducing the multiplexing gain (number of spatially multiplexed substreams) increases the diversity gain, which is predominantly important at low SNR. The CM mode with the highest spectral efficiency giving BER below the target BER for the calculated $SNR_i^{ZF}$ is selected on each substream. The sum of spectral efficiencies is calculated and the whole procedure, of switching off the weakest antenna and calculating new $SNR_i^{ZF}$ ratios and CM modes for the remaining active antennas, is repeated. If the calculated system throughput is higher than for the previous iteration, the iteration is repeated until the throughput of the system starts to decrease. The output of the algorithm is the set of transmit antennas and their CM modes with the highest system throughput.

An algorithm without the outer optimization loop, as was proposed in [6], would use CM modes with very low spectral efficiencies, adding little to the throughput but causing high interference, since the equalizer matrix can be highly ill-conditioned. Therefore adding CM modes with strong error correction coding actually decreases the spectral efficiency of such an algorithm. In the limiting case, if an infinite set of CM modes were available, there would be no antenna selection, since there would always exist a CM mode enabling communication.

Two other antenna selection criteria besides “post-processing SNR” have been proposed in the literature: the “maximum minimum singular value” criterion and the “maximum capacity” criterion [4]. The minimal singular value of the deflated channel matrix gives a lower bound for all $SNR_i^{ZF}$ [4], but in our case we are interested in the exact expression for the post-processing SNR for each transmit antenna. On the other hand the maximum capacity criterion is based on a general capacity formula and is adapted neither to the linear receiver nor to the properties of the available CM modes, and therefore it gives inferior results [7].

## 4. Performance analysis

The system performance is tested for two target BERs, namely $10^{-3}$ and $10^{-6}$, in the uncorrelated Rayleigh fading MIMO channel. The MIMO system consists of either 4 transmit and 4 receive antennas ($M_R=M_T=4$) or 8 receive and 8 transmit antennas ($M_R=M_T=8$). The set of uncoded modulation modes: from BPSK to 1024-QAM with bandwidth efficiencies of 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 bits/s/Hz are applied in simulations. The power is allocated uniformly among active antennas. Preliminary simulations results have shown no significant improvement when power is allocated among transmit antennas applying water-filling algorithm, therefore in this paper we focus only on uniform power distribution among active antennas.

The simulation results obtained are compared to a conventional adaptive single input single output (SISO) system.

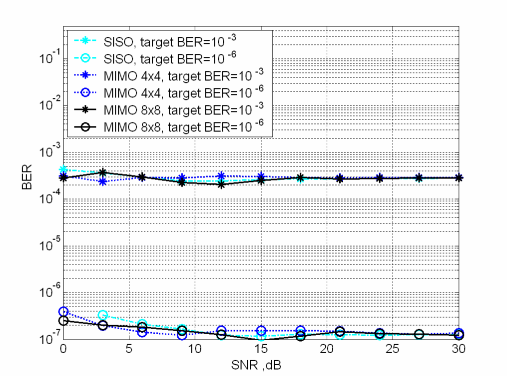

***Figure 3:*** *BER versus SNR.*

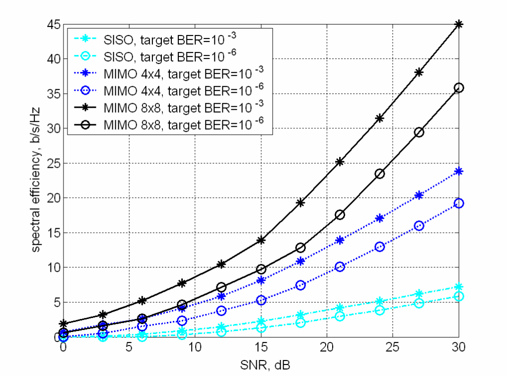

***Figure 4:*** *Spectral efficiency versus SNR.*

The BERs and spectral efficiencies for SISO and MIMO systems are plotted in Fig. 3 and Fig 4. The BER is below the target value and nearly constant in the SNR range considered, from 0 to 30 dB, for all simulated systems. The BER does not noticeable depend on the number of transmit and receive antennas nor on the SNR, but the spectral efficiency is highly dependent on those parameters. A nearly linear increase of system spectral efficiency with the number of antennas can be observed in Fig. 4, as is expected from the theory [1].

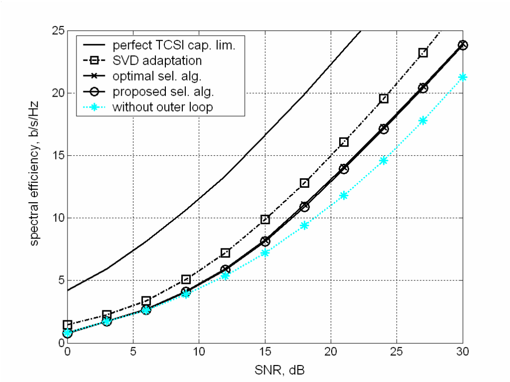

***Figure 5:*** *Spectral efficiency of adaptive MIMO 4 x 4 systems at target BER* $10^{-3}$.

In Fig. 5 we compare proposed algorithm (circles) to the algorithm without the second throughput maximisation loop (stars) [6], exhaustive search optimal selection algorithm (crosses) and MIMO system applying adaptive transmission on eigenmodes (squares) [10] for the MIMO system with four transmit and four receive antennas in the uncorrelated Rayleigh fading channel and target BER $10^{-3}$. All algorithms give the same near constant BER over the entire observed SNR range. At higher SNRs the algorithm proposed significantly outperforms the algorithm without the second loop and its performance is close to the optimal (exhaustive search) selection algorithm. For adaptive transmission on eigenmodes simulation the MIMO channel is decomposed into $N=min(M_T,M_R)$ orthogonal eigenmodes or pipes using the singular value decomposition (SVD) of the channel matrix [1], [10], [11]. Due to the orthogonality of the pipes the methods for ACM techniques known from the SISO systems can be used on each pipe separately. We use the substream and CM mode selection algorithm described on the orthogonal pipes. The orthogonalisation further increases the spectral efficiency, but it has several drawbacks including much larger amount of information transferred in the return channel, increased peak to average power ratio, and higher sensitivity to channel variation and channel mis-estimation [6], [12]. The solid line in Fig. 5 denotes the Shannon channel capacity of MIMO systems for CSI known at the transmitter (TCSI) [1].

## 5. Conclusion

Spatial multiplexing MIMO wireless communication system with adaptive coding-modulation, transmit antenna selection and linear MIMO detection has been proposed and analysed. Both the number and the subset of active transmit antennas is selected according to current CSI in order to maximize the throughput of the system with available CM modes, while keeping the BER below a given threshold. We believe proposed fast suboptimal transmission scheme selection algorithm is close to the optimal selection regardless of the number and the properties of the available CM modes. The selection will be a bit further from optimal if a higher number of transmit antennas is available [13], but in that case the computational complexity of the optimal selection is enormous.

Only straightforward linear detection has been investigated. In transmit antenna selection MIMO systems based on post-processing SNR the performance of linear detection is close to iterative VBLAST detection and not so far from ML detection [6]. ML detection is particularly unsuitable for adaptive rate systems, since the computation time is exponentially dependant on the spectral efficiency. Research on iterative detection with smart ordering based on the expected BER suggests that this is a more promising solution, especially to cope with the channel variation [12].

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