

Modulation-Mode and Power Assignment in SVD-Equalized MIMO Systems

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Dedicated to Prof. Reiner Rockmann on occasion of his 70th birthday

Abstract: Existing bit loading and transmit power allocation techniques are often optimized for maintaining both a fixed transmit power and a fixed target bit-error rate while attempting to maximize the overall data-rate. However, delay-critical real-time interactive applications, such as voice or video transmission, may require a fixed data rate. In this contribution the number of activated layers in a multiple input multiple output (MIMO) system and the number of bits per symbol along with the appropriate allocation of the transmit power are jointly optimized under the constraint of a given fixed data throughput. Our results show that in order to achieve the best bit-error rate, not necessarily all MIMO layers have to be activated.

Keywords: Multiple input multiple output system, singular value decomposition, bit allocation, power allocation, wireless transmission.

1 Introduction

ADAPTIVE MODULATION (AM) is a promising technique to increase the spectral efficiency of wireless transmission systems by adapting the signal parameters, such as modulation constellation or transmit power, dynamically to changing channel conditions [4]. However, in order to comply with the demand on increasing available data rates in particular in wireless technologies, systems with multiple

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transmit and receive antennas, also called MIMO systems (multiple input multiple output), have become indispensable and can be considered as an essential part of increasing both the achievable capacity and integrity of future generations of wireless systems [5, 6]. In general, the most beneficial choice of the number of bits per symbol and the appropriate allocation of the transmit power offer a certain degree of design freedom, which substantially affects the performance of MIMO systems. The well-known water-filling technique is virtually synonymous with adaptive modulation [7, 8, 9, 10, 11, 4] and it is used for maximizing the overall data rate. However, delay-critical applications, such as voice or streaming video transmissions, may require a certain fixed data rate. For these fixed-rate applications it is desirable to design algorithms, which minimize the bit-error rate (BER) at a given fixed data rate. Assuming perfect channel state information at the transmitter side, the channel capacity can only be achieved by using water-pouring procedures. However, in practical application only finite and discrete rates are possible. Therefore in this contribution the efficiency of fixed transmission modes is studied. Against this background, the novel contribution of this paper is that we demonstrate the benefits of amalgamating a suitable choice of activated MIMO layers and number of bits per symbol with the appropriate allocation of the transmit power under the constraint of a given data throughput.

The remaining part of this paper is organized as follows: Section 2 introduces the system model and the considered quality criteria. The proposed solutions of adaptive bit and power allocation are discussed in section 3, while the associated performance results are presented and interpreted in section 4. Section 5 provides some concluding remarks and finally, a short outlook on interesting topics for further work is given in section 6.

2 SDM MIMO Model and Quality Criteria

When considering a non-frequency selective SDM (space division multiplexing) MIMO link composed of n_T transmit and n_R receive antennas, the system is modelled by

$$\mathbf{u} = \mathbf{H} \cdot \mathbf{c} + \mathbf{w} . \quad (1)$$

In (1), \mathbf{u} is the $(n_R \times 1)$ received vector, \mathbf{c} is the $(n_T \times 1)$ transmitted signal vector containing the complex input symbols and \mathbf{w} is the $(n_R \times 1)$ vector of the additive, white Gaussian noise (AWGN) having a variance of U_R^2 for both the real and imaginary parts. Furthermore, we assume that the coefficients of the $(n_R \times n_T)$ channel matrix \mathbf{H} are independently Rayleigh distributed with equal variance and that the number of transmit antennas n_T equals the number of receive antennas n_R . The interference between the different antenna's data streams, which is introduced by

the non-diagonal channel matrix \mathbf{H} , requires appropriate signal processing strategies. Common strategies for separating the data streams are linear equalization at the receiver side or linear pre-equalization at the transmitter side, if channel state information is available. Unfortunately, linear equalization suffers from noise enhancement and linear pre-equalization of the transmit signal from an increase in the transmit power. Both schemes only offer poor power efficiency. Therefore, other signal processing strategies have attracted a lot of interest. Another popular technique is based on the singular value decomposition (SVD) [12] of the system matrix \mathbf{H} , which can be written as $\mathbf{H} = \mathbf{S} \cdot \mathbf{V} \cdot \mathbf{D}^H$, where \mathbf{S} and \mathbf{D}^H are unitary matrices and \mathbf{V} is a real-valued diagonal matrix of the positive square roots of the eigenvalues of the matrix $\mathbf{H}^H \mathbf{H}$ sorted in descending order¹. The SDM MIMO data vector \mathbf{c} is now multiplied by the matrix \mathbf{D} before transmission. In turn, the receiver multiplies the received vector \mathbf{u} by the matrix \mathbf{S}^H . Thereby neither the transmit power nor the noise power is enhanced. The overall transmission relationship is defined as

$$\mathbf{y} = \mathbf{S}^H (\mathbf{H} \cdot \mathbf{D} \cdot \mathbf{c} + \mathbf{w}) = \mathbf{V} \cdot \mathbf{c} + \tilde{\mathbf{w}}. \quad (2)$$

Here, the channel matrix \mathbf{H} is transformed into independent, non-interfering layers having unequal gains.

In general, the quality of data transmission can be informally assessed by using the signal-to-noise ratio (SNR) at the detector's input defined by the half vertical eye opening and the noise power per quadrature component according to

$$\rho = \frac{(\text{Half vertical eye opening})^2}{\text{Noise Power}} = \frac{(U_A)^2}{(U_R)^2}, \quad (3)$$

which is often used as a quality parameter [13]. The relationship between the signal-to-noise ratio $\rho = U_A^2/U_R^2$ and the bit-error probability evaluated for AWGN channels and M -ary Quadrature Amplitude Modulation (QAM) is given by [14, 15]

$$P_{\text{BER}} = \frac{2}{\log_2(M)} \left(1 - \frac{1}{\sqrt{M}} \right) \text{erfc} \left(\sqrt{\frac{\rho}{2}} \right). \quad (4)$$

When applying the proposed system structure, the SVD-based equalization leads to different eye openings per activated MIMO layer ℓ and per transmitted symbol block k according to

$$U_A^{(\ell,k)} = \sqrt{\xi_{\ell,k}} \cdot U_{s\ell}, \quad (5)$$

where $U_{s\ell}$ denotes the half-level transmit amplitude assuming M_ℓ -ary QAM and $\sqrt{\xi_{\ell,k}}$ represents the positive square roots of the eigenvalues of the matrix $\mathbf{H}^H \mathbf{H}$

¹The transpose and conjugate transpose (Hermitian) of \mathbf{D} are denoted by \mathbf{D}^T and \mathbf{D}^H , respectively.

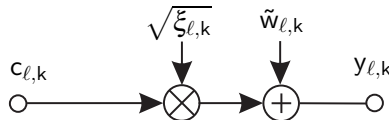


Fig. 1. Resulting system model per MIMO layer ℓ and transmitted data block k

(Fig. 1). Together with the noise power per quadrature component, the SNR per MIMO layer becomes

$$\rho^{(\ell,k)} = \frac{\left(U_A^{(\ell,k)}\right)^2}{U_R^2} = \xi_{\ell,k} \frac{(U_{s\ell})^2}{U_R^2}. \quad (6)$$

Considering QAM constellations, the average transmit power $P_{s\ell}$ per MIMO layer ℓ may be expressed as [16, 17]

$$P_{s\ell} = \frac{2}{3} U_{s\ell}^2 (M_\ell - 1). \quad (7)$$

Combining (6) and (7), the layer-specific SNR results in

$$\rho^{(\ell,k)} = \xi_{\ell,k} \frac{3}{2(M_\ell - 1)} \frac{P_{s\ell}}{U_R^2}. \quad (8)$$

Using the parallel transmission over $L \leq \min(n_T, n_R)$ MIMO layers, the overall mean transmit power becomes $P_s = \sum_{\ell=1}^L P_{s\ell}$, where the number of readily separable layers² is limited by $\min(n_T, n_R)$. In order to transmit at a fixed data rate while maintaining the best possible integrity, i. e. bit-error rate, an appropriate number of MIMO layers has to be used, which depends on the specific transmission mode, as detailed in Tab. 1. In general, the BER per SDM MIMO data vector is dominated by the specific transmission mode and the characteristics of the singular values, resulting in different BERs for the different QAM configurations in Tab. 1. An optimized adaptive scheme would now use the particular transmission mode that results in the lowest BER for each SDM MIMO data vector. This would lead to different transmission modes for different SDM MIMO data vectors and a moderate signaling overhead would result. However, in order to reduce the signalling overhead further, fixed transmission modes are used in this contribution regardless of the channel quality. The bit-error probability per MIMO layer ℓ and transmitted

²It is worth noting that with the aid of powerful non-linear near Maximum Likelihood (ML) sphere decoders it is possible to separate $n_R > n_T$ number of layers [18].

Table 1. Investigated transmission modes

throughput	layer 1	layer 2	layer 3	layer 4
8 bit/s/Hz	256	0	0	0
8 bit/s/Hz	64	4	0	0
8 bit/s/Hz	16	16	0	0
8 bit/s/Hz	16	4	4	0
8 bit/s/Hz	4	4	4	4
12 bit/s/Hz	4096	0	0	0
12 bit/s/Hz	256	16	0	0
12 bit/s/Hz	64	64	0	0
12 bit/s/Hz	64	16	4	0
12 bit/s/Hz	64	4	4	4
12 bit/s/Hz	16	16	16	0
12 bit/s/Hz	16	16	4	4

symbol block k after SVD is given by [13]

$$P_{\text{BER}}^{(\ell,k)} = \frac{2 \left(1 - \frac{1}{\sqrt{M_\ell}}\right)}{\log_2(M_\ell)} \operatorname{erfc} \left(\sqrt{\frac{\xi_{\ell,k}}{2}} \cdot \frac{U_{s\ell}}{U_R} \right). \quad (9)$$

The resulting average bit-error probability per transmitted symbol block k assuming different QAM constellation sizes per activated MIMO layer results in

$$P_{\text{BER}}^{(k)} = \frac{1}{\sum_{v=1}^L \log_2(M_v)} \sum_{\ell=1}^L \log_2(M_\ell) P_{\text{BER}}^{(\ell,k)}. \quad (10)$$

When considering time-variant channel conditions, rather than an AWGN channel, the BER can be derived by considering the different transmission block SNRs. Assuming that the transmit power is uniformly distributed over the number of activated MIMO layers, i. e., $P_{s\ell} = P_s/L$, the half-level transmit amplitude $U_{s\ell}$ per activated MIMO layer results in

$$U_{s\ell} = \sqrt{\frac{3P_s}{2L(M_\ell - 1)}}. \quad (11)$$

The signal-to-noise ratio per data block k and MIMO-layer ℓ , defined in (6), results together with (11) in

$$\rho^{(\ell,k)} = \xi_{\ell,k} \frac{3}{2L(M_\ell - 1)} \frac{P_s}{U_R^2} = \xi_{\ell,k} \frac{3}{L(M_\ell - 1)} \frac{E_s}{N_0}, \quad (12)$$

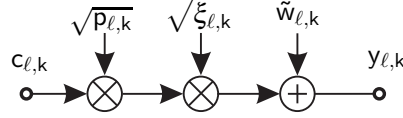


Fig. 2. Resulting system model per MIMO layer ℓ and transmitted data block k including MIMO-layer PA

with

$$\frac{P_s}{U_R^2} = \frac{E_s}{N_0/2} . \quad (13)$$

The BER per activated MIMO layer ℓ and transmitted symbol block k is given by:

$$P_{\text{BER}}^{(\ell,k)} = \frac{2 \left(1 - \frac{1}{\sqrt{M_\ell}}\right)}{\log_2(M_\ell)} \operatorname{erfc} \left(\sqrt{\frac{3 \xi_{\ell,k}}{2L(M_\ell - 1)} \frac{E_s}{N_0}} \right) . \quad (14)$$

The resulting average bit-error probability per transmitted symbol block k assuming different QAM constellation sizes is obtained as

$$P_{\text{BER}}^{(k)} = \frac{2}{R} \sum_{\ell=1}^L \left(1 - \frac{1}{\sqrt{M_\ell}}\right) \operatorname{erfc} \left(\sqrt{\frac{3 \xi_{\ell,k}}{2L(M_\ell - 1)} \frac{E_s}{N_0}} \right) , \quad (15)$$

with

$$R = \sum_{\ell=1}^L \log_2 M_\ell . \quad (16)$$

describing the number of transmitted bits per data block.

3 Adaptive Power Allocation

In systems, where channel state information is available at the transmitter side, the knowledge about how the symbols are attenuated by the channel can be used to adapt the transmit parameters. Power allocation can be used to balance the bit-error probabilities in the activated MIMO layers. Adaptive Power Allocation (PA) has been widely investigated in the literature [7, 8, 11, 13, 19, 20]. The BER of the uncoded MIMO system is dominated by the specific layer having the smallest SNR. As a remedy, a MIMO transmit PA scheme is required for minimizing the overall BER under the constraint of a limited total MIMO transmit power. The proposed PA scheme scales the half-level transmit amplitude $U_{s\ell}$ of the ℓ th MIMO layer by the factor $\sqrt{p_{\ell,k}}$. This results in a transmit amplitude of $U_{s\ell} \sqrt{p_{\ell,k}}$ for each QAM

symbol of the MIMO transmit data vector (Fig. 2). Applying MIMO-layer PA, the half vertical eye opening per MIMO layer ℓ and data block k becomes

$$U_{\text{PA}}^{(\ell,k)} = \sqrt{p_{\ell,k}} \cdot \sqrt{\xi_{\ell,k}} \cdot U_{s\ell} . \quad (17)$$

Now the signal-to-noise ratio, defined in (12), is changed to

$$\rho_{\text{PA}}^{(\ell,k)} = \frac{\left(U_{\text{PA}}^{(\ell,k)}\right)^2}{U_{\text{R}}^2} = p_{\ell,k} \cdot \frac{3\xi_{\ell,k}}{L(M_\ell - 1)} \frac{E_s}{N_0} = p_{\ell,k} \cdot \rho^{(\ell,k)} . \quad (18)$$

Using (4) and (18), along with the MIMO detector's input noise power, the resultant BER per MIMO layer and transmitted data block can be calculated according to

$$P_{\text{BERPA}}^{(\ell,k)} = \frac{2 \left(1 - \frac{1}{\sqrt{M_\ell}}\right)}{\log_2(M_\ell)} \text{erfc} \left(\sqrt{\frac{3 p_{\ell,k} \xi_{\ell,k}}{2L(M_\ell - 1)} \frac{E_s}{N_0}} \right) . \quad (19)$$

Finally, the BER per data block results in

$$P_{\text{BERPA}}^{(k)} = \frac{2}{R} \sum_{\ell=1}^L \left(1 - \frac{1}{\sqrt{M_\ell}}\right) \text{erfc} \left(\sqrt{\frac{3 p_{\ell,k} \xi_{\ell,k}}{2L(M_\ell - 1)} \frac{E_s}{N_0}} \right) . \quad (20)$$

The aim of the forthcoming discussions is now the determination of the values $\sqrt{p_{\ell,k}}$ for the activated MIMO layers.

3.1 Optimum power allocation

A common strategy is to use the Lagrange multiplier method in order to find the optimal value of $\sqrt{p_{\ell,k}}$ for each MIMO layer ℓ and data block k . The Lagrangian cost function $J(p_{1,k}, \dots, p_{L,k})$ may be expressed as

$$J(p_{1,k}, \dots, p_{L,k}) = \frac{2}{R} \sum_{\ell=1}^L \left(1 - \frac{1}{\sqrt{M_\ell}}\right) \text{erfc} \left(\sqrt{\frac{3 p_{\ell,k} \xi_{\ell,k}}{2L(M_\ell - 1)} \frac{E_s}{N_0}} \right) + \lambda B_L , \quad (21)$$

where λ is the Lagrange multiplier [11]. The parameter B_L in (21) describes the boundary condition taking the transmit power restriction into account. The transmit power per activated MIMO layer ℓ and data block k including PA results in

$$P_{\text{PA}s}^{(l,k)} = \frac{2}{3} U_{s\ell}^2 p_{\ell,k} (M_\ell - 1) . \quad (22)$$

With the half-level transmit amplitude $U_{s\ell}$ defined in (11), the transmit power per activated MIMO layer is given by

$$P_{\text{PA}s}^{(\ell,k)} = \frac{P_s}{L} p_{\ell,k} . \quad (23)$$

From the limitation of the transmit power according to

$$\sum_{\ell=1}^L P_{\text{PA}s}^{(\ell,k)} - P_s = 0 \quad (24)$$

follows

$$\frac{P_s}{L} \sum_{\ell=1}^L p_{\ell,k} - P_s = 0 . \quad (25)$$

In order to limit the total transmit power, the following auxiliary condition can be formulated:

$$B_L = \sum_{\ell=1}^L p_{\ell,k} - L = 0 . \quad (26)$$

As solution for the power allocation parameter $p_{\ell,k}$ per activated MIMO layer ℓ and data block k the relationship

$$p_{\ell,k} = \left(\frac{E_s}{N_0} \right)^{-1} \frac{L(M_\ell - 1)}{3\xi_{\ell,k}} \mathbf{W} \left(\frac{18}{\pi} \left(\frac{\xi_{\ell,k}}{\lambda RL(M_\ell + \sqrt{M_\ell})} \frac{E_s}{N_0} \right)^2 \right) , \quad (27)$$

is obtained [21], where $\mathbf{W}(x)$ describes the Lambert W function [22], with

$$\mathbf{W}(x) \cdot e^{\mathbf{W}(x)} = x . \quad (28)$$

The parameter λ can be calculated by insertion of (27) into (26) and numeric analysis. With calculated λ the optimal $p_{\ell,k}$ can be determined using (27).

3.2 Equal-SNR power allocation

Again, a common strategy is to use the Lagrange multiplier method in order to find the optimal value of $\sqrt{p_{\ell,k}}$ for each MIMO layer ℓ and each data block k , which often leads to excessive-complexity optimization problems [13]. Therefore, suboptimal power allocation strategies having a lower complexity are of common interest [13, 11]. A natural choice is to opt for a PA scheme, which results in an identical signal-to-noise ratio

$$\rho_{\text{PAequal}}^{(\ell,k)} = \frac{\left(U_{\text{PAequal}}^{(\ell,k)} \right)^2}{U_{\text{R}}^2} = p_{\ell,k} \cdot \rho^{(\ell,k)} \quad (29)$$

for all activated MIMO layers per data block k , i. e. in

$$\rho_{\text{PAequal}}^{(\ell,k)} = \text{constant} \quad \ell = 1, 2, \dots, L \quad . \quad (30)$$

The power to be allocated to each activated MIMO layer ℓ and transmitted data block k can be shown to be calculated as follows [13]:

$$p_{\ell,k} = \frac{(M_\ell - 1)}{\xi_{\ell,k}} \cdot \frac{L}{\sum_{v=1}^L \frac{(M_v - 1)}{\xi_{v,k}}} \quad . \quad (31)$$

Taking (31) and (11) into account, for each symbol of the transmitted MIMO symbol vector the same half vertical eye opening of

$$U_{\text{PAequal}}^{(\ell,k)} = \sqrt{p_{\ell,k}} \cdot \sqrt{\xi_{\ell,k}} \cdot U_{s\ell} = \sqrt{\frac{3P_s}{2 \sum_{v=1}^L \frac{(M_v - 1)}{\xi_{v,k}}}} \quad (32)$$

can be guaranteed ($\ell = 1, \dots, L$), i. e.,

$$U_{\text{PAequal}}^{(\ell,k)} = \text{constant} \quad \ell = 1, 2, \dots, L \quad . \quad (33)$$

When assuming an identical detector input noise variance for each channel output symbol, the above-mentioned equal quality scenario (30) is encountered, i. e.,

$$\rho_{\text{PAequal}}^{(\ell,k)} = \frac{\left(U_{\text{PAequal}}^{(\ell,k)} \right)^2}{U_R^2} = \frac{E_s}{N_0} \frac{3}{\sum_{v=1}^L \frac{(M_v - 1)}{\xi_{v,k}}} \quad . \quad (34)$$

Analyzing (34) for a given SDM MIMO data block, nearly the same BER can be achieved on all activated MIMO layer. However, taking the time-variant nature of the transmission channel into account, different BERs arise for different SDM MIMO data blocks. Therefore, the BER of the MIMO system is mainly dominated by the data blocks having the lowest SNR's. In order to overcome this problem, the number of transmit or receive antennas has to be increased or coding over the different data blocks should be used [3].

4 Results

In this contribution fixed transmission modes are used regardless of the channel quality. Assuming predefined transmission modes, a fixed data rate can be guaranteed. The obtained BER curves are depicted in Fig. 3–5 for the different QAM

constellation sizes and MIMO configurations of Tab. 1, when transmitting at a bandwidth efficiency of 12 and 8 bit/s/Hz, respectively³. Assuming a uniform

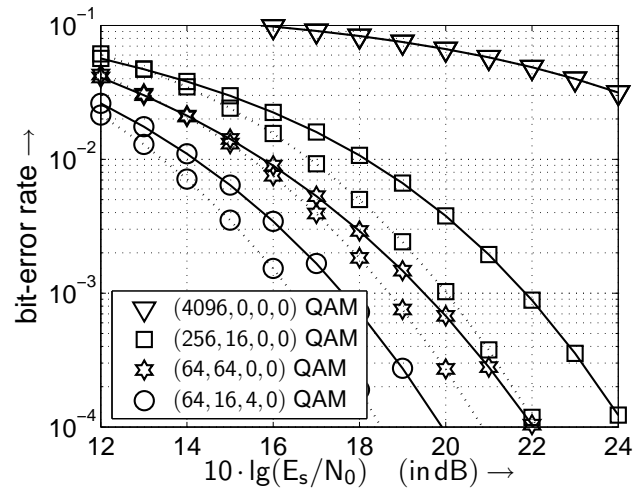


Fig. 3. BER with PA (dotted line) and without PA (solid line) when using the transmission modes introduced in Tab. 1 and transmitting 12 bit/s/Hz over non-frequency selective channels

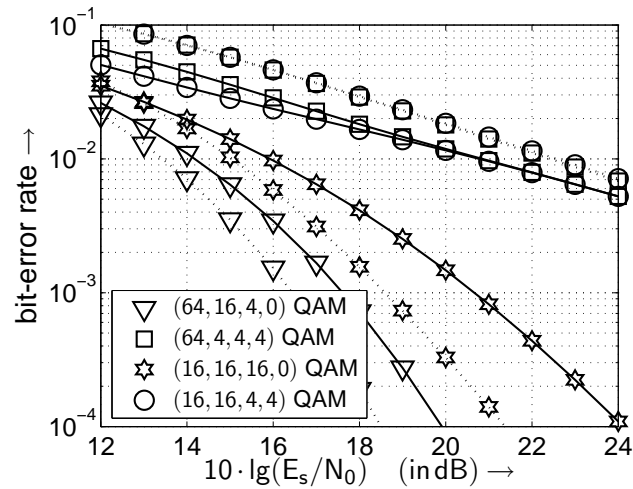


Fig. 4. BER with PA (dotted line) and without PA (solid line) when using the transmission modes introduced in Tab. 1 and transmitting 8 bit/s/Hz over non-frequency selective channels

distribution of the transmit power over the number of activated MIMO layers, it

³The expression $\lg(\cdot)$ is considered to be the short form of $\log_{10}(\cdot)$.

turns out that not all MIMO layers have to be activated in order to achieve the best BERs. More explicitly, our goal is to find that specific combination of the QAM mode and the number of MIMO layers, which gives the best possible BER performance at a given fixed bit/s/Hz bandwidth efficiency. The E_s/N_0 value required by each scheme at BER 10^{-4} was extracted from Fig. 3–5 and the best systems are shown in bold in Tab. 1.

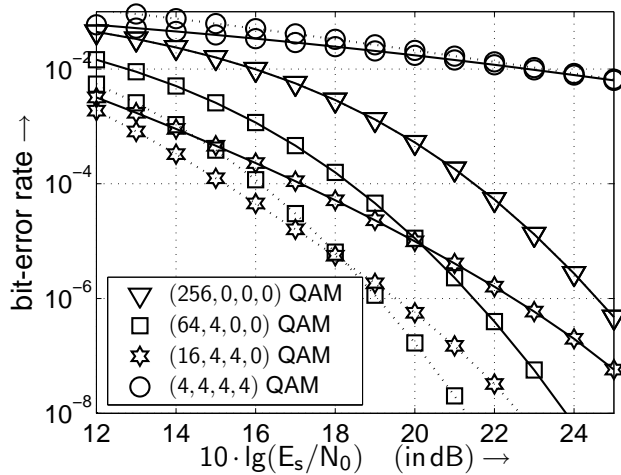


Fig. 5. BER with PA (dotted line) and without PA (solid line) when using the transmission modes introduced in Tab. 1 and transmitting 8 bit/s/Hz over non-frequency selective channels

Allowing a low signaling overhead, an adaptive choice of the transmission modes can be carried out. Since the BER per SDM MIMO data block is dominated by the chosen transmission mode and the distribution of the singular values, the different transmission modes, as depicted in Tab. 1, lead to different BERs per SDM MIMO data block. An adaptive modulation scheme would now use the specific transmission mode that results in the lowest BER per data block. As depicted in Fig. 6, the adaptive choice of the transmission mode outperforms the fixed modes at the cost of a small signaling overhead.

Further improvements are possible by taking the adaptive allocation of the transmit power into account. The differences between the optimal and the suboptimal equal SNR PA as highlighted in Fig. 7 and show a negligible performance gap between the optimal and the equal SNR PA. The only difference between the optimum PA and the equal SNR PA is the consideration of the factor $(1 - 1/\sqrt{M_\ell})$ by the optimum PA. However, their influence, introduced by the layer-specific QAM constellation sizes, is by far too small to generate remarkable differences in the performance. Furthermore, from Fig. 3–5 we see that unequal PA is only effective

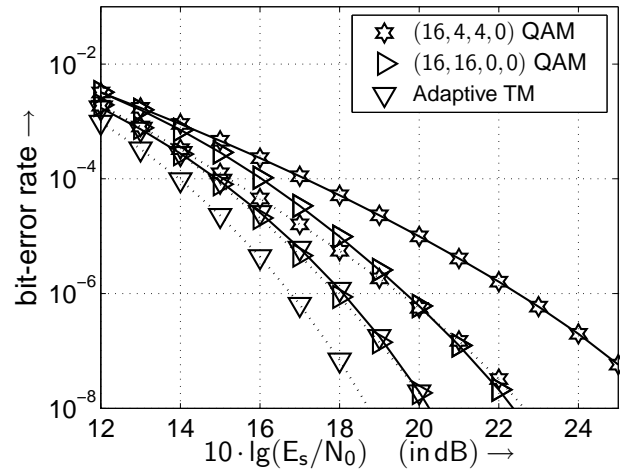


Fig. 6. BER with PA (dotted line) and without PA (solid line) when using the transmission modes (TM) introduced in Tab. 1 and transmitting 8 bit/s/Hz over non-frequency selective channels ($\nabla \triangleq$ adaptive choice of the transmission mode)

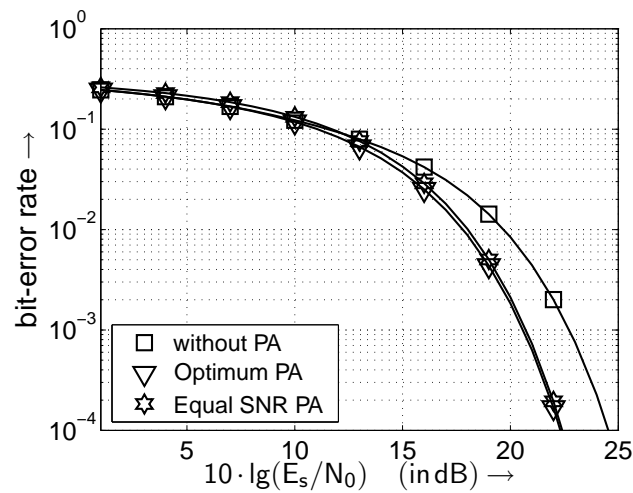


Fig. 7. Different PA solutions on an exemplarily considered channel ($L = 2, M_1 = 64, M_2 = 4, \xi_1 = 1.8, \xi_2 = 0.6$) when transmitting 8 bit/s/Hz over a non-frequency selective channel

in conjunction with the optimum number of MIMO layers. Using all MIMO layers, our PA scheme would assign much of the total transmit power to the specific symbol positions per data block having the smallest singular values and hence the overall performance would deteriorate.

5 Conclusion

Bit and power loading in MIMO systems were investigated. It turned out, that the choice of the number of bits per symbol as well as the number of activated MIMO layer substantially affects the performance of a MIMO system, suggesting that not all MIMO layers have to be activated in order to achieve the best BERs. In particular, different power allocation options were presented. The main goal was to find that specific combination of the QAM mode and the number of MIMO layers, which gives the best possible BER performance at a given fixed bit/s/Hz bandwidth efficiency. The E_s/N_0 value required by each scheme at BER 10^{-4} was extracted from computer simulations and the best systems are shown in bold in Tab. 1.

6 Outlook

Wireless MIMO systems currently are a very dynamic field of research. Therefore there are a lot of interesting topics open for further work, which can be derived from the results of this contribution: Bit and power loading for coded MIMO systems are of great practical interest as demonstrated in [3] or [1]. In addition to the currently very popular wireless MIMO systems, multiple-input multiple-output channels are observed in a variety of transmission links and network parts. Currently, fixed access networks are mainly constituted of multi-pair copper cables which contain a number of wire pairs. These copper cables then by their nature compose a MIMO channel. Cables or cable binders can be treated as MIMO channels and crosstalk relations are taken into account for example by crosstalk equalization schemes [23] and they are exploited in the case of dynamic spectrum management (DSM) [24, 25], which is currently gaining a growing practical interest. Crosstalk in multi-pair copper cables has long been seen as a possible application for MIMO techniques [26].

Another important type of a fixed network medium is the optical fibre, where single- and multi-mode fibres are distinguished. In particular optical multi-mode fibres guide light of different modes: Therefore the multi-mode fibre can be interpreted as a MIMO channel. This is rarely discussed in the literature, since in almost all relevant transmission cases nowadays single-mode fibres are deployed due to their superior transmission performance. However, in case of fibre deployment over short distances (e. g. in-house networks for high data rates) the multi-mode fibre technology eventually may become more popular again (due to the cost advantages of the multi-mode fibre and the associated components compared to single-mode fibres and optical components). If in case of practical relevance – in particular in the optical fibre case – results from the currently very dynamic research on wire-

less and wireline MIMO (DSM) techniques can be adopted and adapted to the fixed optical line problems, synergy effects and considerable improvements are expected.

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