ANALYSIS OF MIMO SYSTEMS WITH ANTENNAS CORRELATION WITH LINEAR AND NON-LINEAR SPATIAL DISTRIBUTION

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Keywords: Multiple Input Multiple Output, Channel Capacity, Bit-error Rate, Antennas Correlation, Wireless Communication.

Abstract: Multiple input multiple output (MIMO) techniques for wireless communication systems have attracted in the last years huge research activity due to the possibility of improving the link performance by increasing the channel capacity and decreasing the bit-error rate (BER). In order to be able to define the benefits of these MIMO techniques it is required to properly characterize the features of the communication channel in the various properties and disturbances. Due to those effects, appropriate signal processing techniques are needed to eliminate or diminish their effects. Furthermore, the use of multiple antennas both at the transmit and the receive front-ends introduces a correlation effect between antennas due to their proximity producing interference. In consequence, the BER increases and the channel capacity decreases. The goal of the present contribution is to analyze the system performance under different spatial antennas distributions for Multi-User (MU) MIMO systems in correlated fading channels.

1 INTRODUCTION

The MIMO term refers to a technique which takes advantage of the spatial dimension of the underlying wireless channel by using multiple antennas at both the transmit (Tx) and the receive (Rx) sides transmitting different data streams through each antenna at the same time and the same frequency. Multiple transmitting and receiving antennas are capable to reduce the error probability and increase the communication channel capacity without any bandwidth extensions. Since the capacity of MIMO systems increases linearly with the minimum number of antennas at both, the transmitter as well as the receiver side, they have attracted substantial attention (McKay and Collings, 2005), (Mueller-Weinfurtner, 2002) and can be considered as an essential part of increasing both the achievable capacity and integrity of future generations of wireless systems (Kühn, 2006), (Zheng and Tse, 2003).

The technical premise is to send different data signals through the various transmit antennas, but at the same carrier frequency and the same time. In this way, independent channels between different Tx and Rx paths are formed to achieve spatial diversity or space division multiplexing. Furthermore, this technique provides the possibility to choose the number of bits per symbol to be transmitted through each path, given a certain number of activated MIMO Tx-Rx paths (layers) for exploiting the space dimension obtaining in this way a certain degree of freedom and hence having the possibility to implement an adaptive modulation scheme which depends on the particular conditions of the activated layers (Zhou et al., 2005).

Multi-User MIMO (MU-MIMO) systems refers to a link configuration comprising a base station with multiple transmit and receive antennas providing access to multiple users (fixed or mobile), each one equipped with multiple antennas. The analysis described in this paper focuses on the downlink segment.

MIMO systems have emerged as a promising technique to achieve high transmission capacities in wireless communication systems. MIMO systems feature a stronger dependency with the propagation channel conditions than single input single output (SISO) systems present; however MIMO systems are capable to reduce the bit-error probability and increase the communication channel capacity by exploiting received multipath signals without increasing

Cano-Broncano F., Benavente-Peces C., Ahrens A., Javier Ortega-González F. and Manuel Pardo-Martín J..
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DOI: 10.5220/0003810102780283
In *Proceedings of the 2nd International Conference on Pervasive Embedded Computing and Communication Systems* (PECCS-2012), pages 278-283
ISBN: 978-989-8565-00-6

neither the required transmitted power nor the signal bandwidth.

The communication channel is affected by various disturbances: attenuation, noise, interferences, multipath, fading. Additionally, due to the proximity of the multiple antennas at any of the ends, the correlation effect appears affecting the channel characteristics and pouring the communication link performance. Several studies have been carried out to characterize antenna correlation (Oestges, 2006; Narasimhan, 2003; Asztly, 1996), providing models which allow analyzing its effects on the communication system performance. Typically, in practical communication systems, the separation between different antennas at the base stations is set ten times the carrier wavelength while wireless mobile reception station antennas are set to be separated by one carrier wavelength to guarantee a proper link performance.

In order to reach the full MIMO system performance, appropriate signal processing techniques should be applied. A popular technique largely used is the singular value decomposition (SVD) (Haykin, 2002). Through the appropriate use of such technique at both the Tx and Rx sides performing some preprocessing and post-processing respectively, channel multipath interference as well as multi-user interferences can be eliminated (Benavente-Peces et al., 2010). To obtain the full benefits of the SVD use, this technique requires perfect channel state information at both the transmitter and the receiver side, which produces some communication overhead. The channel state has to be computed at the receiver side by transmitting a training sequence and some overhead is produced when delivering the channel state information back to the transmitter side. The main contribution of this work is the analysis of the downlink of a MU-MIMO system under antennas correlation (Durgin and Rappaport, 1999; Zelst and Hammerschmidt, 2002; Ahrens and Benavente-Peces, 2011).

The remaining part of this contribution is organized as follows: Section 2 describes the MU-MIMO model including antenna correlation. Section 3 introduces the spatial antenna distribution and models two cases studies for demonstration purposes. The associated performance results are presented and commented in section 4. Finally, in section 5 the concluding remarks are discussed.

2 MULTIUSER SYSTEM MODEL

The system model considered in this work consists of a single base station (BS) supporting K mobile stations (MSs). The BS is equipped with n_{T} transmit antennas, while the kth (with $k = 1, \ldots, K$) MS has $n_{\mathrm{R}\,k}$ receive antennas, i. e. the total number of receive antennas including all K MSs is given by $n_{\mathrm{R}} = \sum_{k=1}^{K} n_{\mathrm{R}\,k}$. The $(n_{\mathrm{R}\,k} \times 1)$ user specific symbol vector $\mathbf{c}_k$ to be transmitted by the BS is given by

$$\mathbf{c}_k = \left(c_{k,1}, c_{k,2}, \ldots, c_{k,n_{\mathrm{R}\,k}}\right)^{\mathrm{T}} \quad . \tag{1}$$

The vector $\mathbf{c}_k$ is preprocessed before its transmission by multiplying it by the $(n_{\mathrm{T}} \times n_{\mathrm{R}\,k})$ DL preprocessing matrix $\mathbf{R}_k$ and resulting the $(n_{\mathrm{T}} \times 1)$ user-specific transmit vector

$$\mathbf{s}_k = \mathbf{R}_k\,\mathbf{c}_k \quad . \tag{2}$$

After DL transmitter preprocessing, the n_{T}-component signal $\mathbf{s}$ transmitted by the BS to the K MSs results in

$$\mathbf{s} = \sum_{k=1}^{K} \mathbf{s}_k = \mathbf{R}\,\mathbf{c} \quad , \tag{3}$$

with the $(n_{\mathrm{T}} \times n_{\mathrm{R}})$ preprocessing matrix

$$\mathbf{R} = (\mathbf{R}_1, \mathbf{R}_2, \ldots, \mathbf{R}_K) \quad . \tag{4}$$

In (3), the overall $(n_{\mathrm{R}} \times 1)$ transmitted DL data vector $\mathbf{c}$ combines all K DL transmit vectors $\mathbf{c}_k$ (with $k = 1, 2, \ldots, K$) and is given by

$$\mathbf{c} = \left(\mathbf{c}_1^{\mathrm{T}}, \mathbf{c}_2^{\mathrm{T}} \ldots, \mathbf{c}_K^{\mathrm{T}}\right)^{\mathrm{T}} \quad . \tag{5}$$

At the receiver side, the $(n_{\mathrm{R}\,k} \times 1)$ vector $\mathbf{u}_k$ of the kth MS is given by

$$\mathbf{u}_k = \mathbf{H}_k\,\mathbf{s} + \mathbf{n}_k = \mathbf{H}_k\,\mathbf{R}\,\mathbf{c} + \mathbf{n}_k \quad . \tag{6}$$

and can be expressed by

$$\mathbf{u}_k = \mathbf{H}_k\,\mathbf{R}_k\,\mathbf{c}_k + \sum_{i=1, i \neq k}^{K} \mathbf{H}_k\,\mathbf{R}_i\,\mathbf{c}_i + \mathbf{n}_k \quad , \tag{7}$$

where the MSs received signals experience both multi-user and multi-antenna interferences. In (6) and (7), the $(n_{\mathrm{R}\,k} \times n_{\mathrm{T}})$ channel matrix $\mathbf{H}_k$ connects the n_{T} BS specific transmit antennas with the $n_{\mathrm{R}\,k}$ receive antennas of the kth MS.

It is quite common to assume that the coefficients of the $(n_{\mathrm{R}\,k} \times n_{\mathrm{T}})$ channel matrix $\mathbf{H}_k$ are independent and Rayleigh distributed with equal variance. However, in many cases correlations between the transmit antennas as well as between the receive antennas can't be neglected. There are several methods to model and characterize the antenna signals correlation effects on the MIMO channel model in the Rayleigh flat-fading channel case. In this work it is assumed that the correlation among receive antennas is independent of the correlation between transmit antennas.

The way to include the antenna signal correlation effect on the MIMO channel model for Rayleigh flat-fading like channels is described in (Durgin and Rappaport, 1999; Zelst and Hammerschmidt, 2002) and results in

$$\mathbf{H}_k = \mathbf{H}_{\mathrm{Rx}}^{1/2} \cdot \mathbf{G} \cdot \mathbf{H}_{\mathrm{Tx}}^{1/2}, \tag{8}$$

where $\mathbf{G}$ is a $(n_{\mathrm{R}k} \times n_{\mathrm{T}})$ uncorrelated channel matrix with independent, identically distributed complex Gaussian zero-mean unit variance elements and where $(\cdot)^{1/2}$ stands for the square root of a matrix. The $(n_{\mathrm{R}k} \times n_{\mathrm{R}k})$ matrix $\mathbf{H}_{\mathrm{Rx}}$ is used to model the correlation among the kth MS receive antennas. On the other hand, the $(n_T \times n_T)$ transmit correlation matrix $\mathbf{H}_{\mathrm{Tx}}$ models the correlation among the transmit antennas.

The interference, which is introduced by the channel matrix $\mathbf{H}_k$, requires appropriate signal processing strategies. A popular technique is based on the SVD of the system matrix $\mathbf{H}_k$ as described in (Ahrens and Benavente-Peces, 2010). Therein, after pre- and post-processing of the transmitted and received signal vectors, the user-specific decision variables result in

$$\mathbf{y}_k = \mathbf{V}_{k\mathrm{u}} \, \mathbf{P}_k \, \mathbf{c}_k + \mathbf{w}_k \ , \tag{9}$$

where interferences between the different antenna data streams as well as MUI (multi-user interference) imposed by the other users are avoided as shown in (Ahrens and Benavente-Peces, 2010). In (9), the $(n_{\mathrm{R}k} \times n_{\mathrm{R}k})$ diagonal matrix $\mathbf{V}_{k\mathrm{u}}$ contains the non-zero square roots of the eigenvalues of $\mathbf{H}_k^{\mathrm{H}} \mathbf{H}_k$, e. g.,

$$\mathbf{V}_{k\mathrm{u}} = \begin{bmatrix} \sqrt{\xi_{k,1}} & 0 & \cdots & 0 \\ 0 & \sqrt{\xi_{k,2}} & \ddots & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ 0 & 0 & \cdots & \sqrt{\xi_{k,n_{\mathrm{R}k}}} \end{bmatrix}, \tag{10}$$

and the user-specific $(n_{\mathrm{R}k} \times n_{\mathrm{R}k})$ diagonal power allocation matrix is given by

$$\mathbf{P}_k = \begin{bmatrix} \sqrt{p_{k,1}} & 0 & \cdots & 0 \\ 0 & \sqrt{p_{k,2}} & \ddots & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ 0 & 0 & \cdots & \sqrt{p_{k,n_{\mathrm{R}k}}} \end{bmatrix} \tag{11}$$

and simplifies to $\mathbf{P}_k = \sqrt{\beta}\,\mathbf{I}_{n_{\mathrm{R}k} \times n_{\mathrm{R}k}}$ for the power equal distribution case with the parameter $\sqrt{\beta}$ taking the transmit-power constraint into account as highlighted in (Ahrens and Benavente-Peces, 2010). Finally the additive, white Gaussian noise (AWGN) vector is given by $\mathbf{w}_k$. The resulting system model is depicted in Fig. 1 In order to transmit at a fixed data rate while maintaining the best possible integrity, i. e., bit-error rate, an appropriate number of user-specific

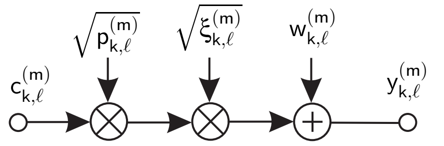

Figure 1: Resulting kth user-specific system model per MIMO layer ℓ (with $\ell = 1, 2, \ldots, n_{\mathrm{R}k}$) and per transmitted symbol block m

Table 1: Investigated user-specific QAM 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

MIMO layers has to be used, which depends on the specific transmission mode, as detailed in Table 1 for the exemplarily investigated case in which a multiuser system with two users is considered ($n_{\mathrm{R}k} = 4$ (with $k = 1, 2), K = 2, n_{\mathrm{R}} = n_{\mathrm{T}} = 8$). In order to avoid any signalling overhead, fixed transmission modes are used in this contribution regardless of the channel quality (Ahrens and Lange, 2008).

3 ANTENNAS' SPATIAL DISTRIBUTION

Spatial multiplexing is a method to reach the theoretical maximum channel capacity with a reasonable implementation complexity. Spatial multiplexing achieves the best performance in rich-scattering channels in which the paths suffer from uncorrelated fading (Narasimhan, 2003). In this contribution, we analyze and simulate two different antennas spatial distributions (linear and non-linear uniform antennas distributions) for a MIMO system composed of $n_{\mathrm{T}} = 4$ transmit and $n_{\mathrm{R}} = 4$ receive antennas (single-user MIMO link, $K = 1$). The goal is showing the high dependency of both separation and distribution on the correlation degree and the impact of antennas correlation on the communication link performance.

3.1 Antennas with Linear Spatial Distribution

In this case it is considered that the antennas are linearly distributed and equally spaced where this spacing is set to Δ_{t} and Δ_{r} (given in wavelength units) at the transmitter and receiver side, respectively. Fig. 2 represents the antennas' spatial distribution.

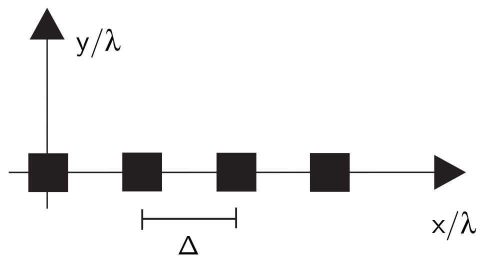

Figure 2: Linear antennas distribution.

3.2 Antennas with Non-linear Spatial Distribution

In this second case of study a non-linear antenna array distribution with equal distance between adjacent elements is assumed. We have imposed in this exemplarily case that the chosen distribution is a square with one antenna at each corner. Again, the implemented MU-MIMO system contains $n_T = 4$ transmit and $n_R = 4$ receive antennas (single-user MIMO link, $K = 1$). Fig. 3 shows the geometrical disposition of the antennas to be evaluated.

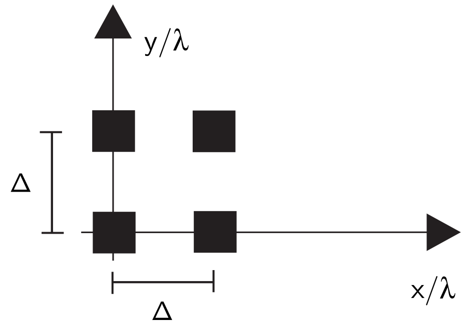

Figure 3: Non-linear antennas distribution.

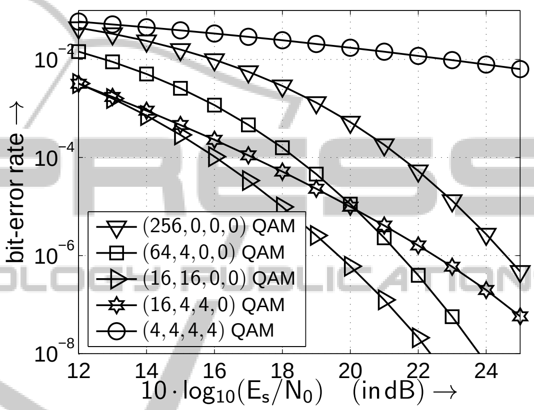

Figure 4: BER when using the transmission modes introduced in Tab. 1 and transmitting 8 bit/s/Hz over uncorrelated frequency non-selective channels.

4 RESULTS

In this contribution a MIMO system in the absence and the present of antenna correlation effects has been analyzed including the consideration of linear and non-linear antennas spacing for some exemplarily fixed transmission modes (described in Tab. 1).

4.1 Single-user MIMO

Considering a frequency non-selective SDM (spatial division multiplexing) single-user MIMO link ($K = 1$) composed of $n_T = 4$ transmit and $n_R = 4$ receive antennas, the resulting BER curves are depicted in Fig. 4 for the different transmission modes of Tab. 1, when transmitting at a bandwidth efficiency of 8 bit/s/Hz.

Assuming a uniform distribution of the transmit power over the number of activated MIMO layers, it turns out that not all MIMO layers have to be activated in order to achieve the best BERs. Fig. 5 shows the probability density function (pdf) of the resulting singular values in the case of an uncorrelated MIMO channel with $n_T = 4$ transmit and $n_R = 4$ receive antennas. When considering a single-user MIMO system ($K = 1$) in the presence of antenna correlation, assuming a linear distribution of both the transmit and receive antennas, and considering that the transmission is performed at a carrier frequency at 2.4 GHz with an antenna separation at the transmit side (BS) of 10 times the wavelength and an antenna separation at the receive side (MS) of 4 times the wavelength, the resulting probability distribution function of the computed singular values is depicted in Fig. 6. Comparing the distribution of the singular-values depicted in Fig. 5 and 6, the correlation shifts the pdf of the largest singular-value to higher values at the cost of the remaining layers. In consequence, the probability of using a reduced number of layers for transmitting data becomes larger in the presence of antenna correlation. Thus, taking the correlated MIMO channel instead of the uncorrelated one into consideration, we observe that the influence of the layer with the largest weighting factor increases.

Decreasing the distance between the receive antennas increases the correlation effect. Fig. 8 highlights the resulting BER for some exemplarily transmission modes (from those in Tab. 1) when diminishing the antennas spacing with respect to the previous cases. In comparison with the results in Fig. 7

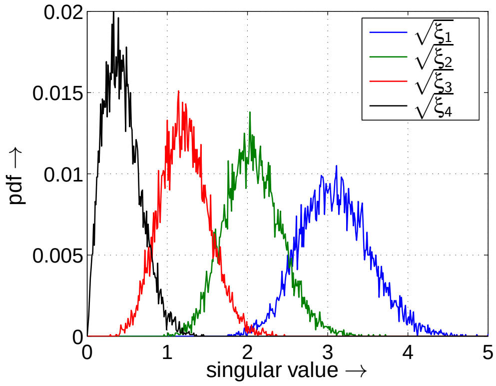

Figure 5: PDF (probability density function) of the layer-specific amplitudes $\sqrt{\xi_\ell}$ for uncorrelated frequency non-selective MIMO channels.

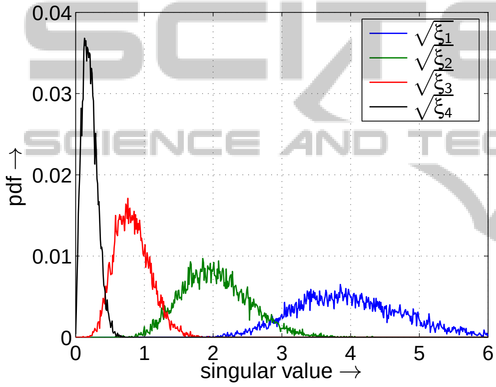

Figure 6: PDF (probability density function) of the layer-specific amplitudes $\sqrt{\xi_\ell}$ for correlated frequency non-selective MIMO channels (linear distribution of both the transmit and receive antennas with $\Delta_t = 10$ and $\Delta_r = 4$).

it is concluded that the shorter the distance between receive antennas the larger the BER and finally the link performance. Furthermore, continuing with the reasoning described above it is concluded that not all MIMO layers must be activated in order to obtain the best results. Concerning the relation between the best performing transmission modes and the probability distribution function of the singular values, the high dependency of the transmission mode with the largest singular value can be remarked. This dependency increases with the correlation degree, the larger the correlation the higher the dependency. In consequence, as the correlation becomes stronger, the probability to use a lower number of layers increases.

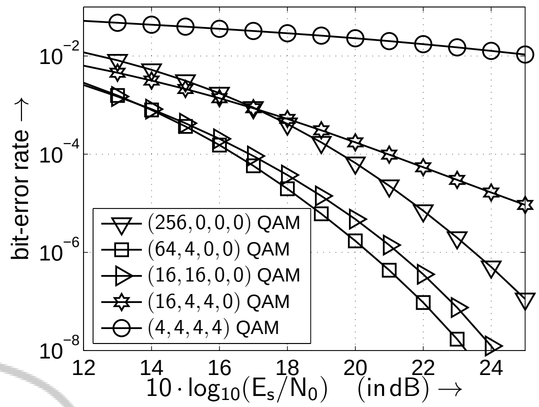

Figure 7: BER when using the transmission modes introduced in Tab. 1 and transmitting 8 bit/s/Hz over correlated frequency non-selective channels (linear distribution of both the transmit and receive antennas with $\Delta_t = 10$ and $\Delta_r = 4$).

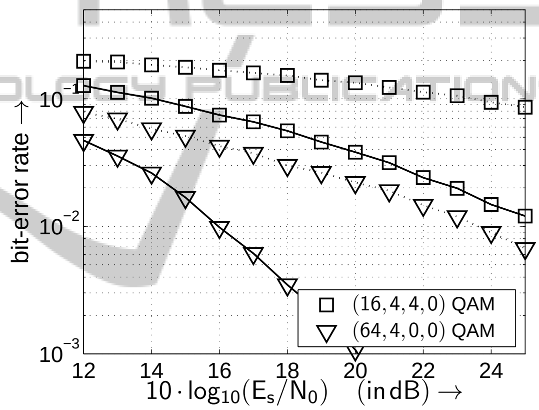

Figure 8: BER with linear antenna distribution (solid line) and with non-linear antenna distribution (dotted line) when using the transmission modes introduced in Tab. 1 and transmitting 8 bit/s/Hz over correlated frequency non-selective channels ($\Delta_t = 10$ and $\Delta_r = 0{,}1$).

4.2 Multi-user MIMO

The parameters of the exemplarily studied two-users MIMO system are chosen as follows: $n_{Rk} = 4$ (with $k = 1,2$), $K = 2, n_R = n_T = 8$. The obtained user-specific BER curves are depicted in Fig. 9 for the different QAM constellation sizes and MIMO configurations in Tab. 1 and confirm the results obtained within the single-user system ($K = 1$). Assuming a uniform distribution of the transmit power along the number of activated MIMO layers, it still turns out that not all MIMO layers have to be activated in order to achieve the best BERs.

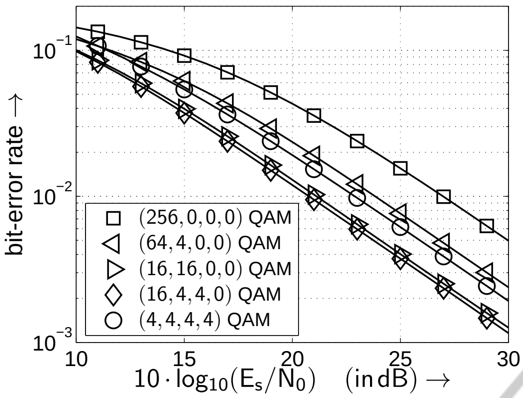

Figure 9: SVD-based user-specific BERs when using the transmission modes introduced in Table 1 and transmitting 8 bit/s/Hz over uncorrelated frequency non-selective channels.

5 CONCLUSIONS

This contribution has analyzed and simulated a MU-MIMO system composed of n_T transmit and n_R receive antennas in conjunction with SVD-assisted signal processing and taking into account the correlation effect among antennas both at the transmit and receive sides. Additionally it was assumed a uniform distribution of the transmit power along the MIMO system activated layers.

By comparing the results obtained from computer simulations it can be concluded that in the presence of correlation among antennas, in the considered non-linear spatial distribution (square spacing in the example) the bit error rate increases for a given fixed SNR (signal-to-noise-ratio), taking as reference the case in which no correlation is present into consideration. Moreover, that increment in the BER is larger than the one produced when using an antenna linear distribution affected by correlation.

Consequently, for a fixed bit-error rate the linear distribution is able to give better results than the squared distribution. This is due to the reduction of the dependency with neighbours antennas as the separations between them become larger. Additionally we observe that for reaching the best performance it is not required that all layers were activated.

REFERENCES

Ahrens, A. and Benavente-Peces, C. (2010). Modulation-Mode and Power Assignment for SVD-assisted and Iteratively Detected Downlink Multiuser MIMO Systems. In *International Conference on Wireless Information Networks and Systems (WINSYS)*, pages 107–114, Athens (Greece).

Ahrens, A. and Benavente-Peces, C. (2011). Modulation-Mode and Power Assignment for SVD-assisted Downlink Multiuser MIMO Systems. In *International Conference on Pervasive and Embedded Computing and Communication Systems (PECCS)*, pages 333–338, Algarve (Portugal).

Ahrens, A. and Lange, C. (2008). Modulation-Mode and Power Assignment in SVD-equalized MIMO Systems. *Facta Universitatis (Series Electronics and Energetics)*, 21(2):167–181.

Asztly, D. (1996). *On Antenna Arrays in Mobile Communication Systems Fast Fading and GSM Base Station Receiver Algorithms*. PhD thesis, Royal Institute of Technology, Stockholm.

Benavente-Peces, C., Cano-Broncano, F., Aust, S., and Ahrens, A. (2010). Modulation-Mode Assignment for SVD-assisted Multiuser MIMO Systems with Correlations. In *18th International Conference on Microwave, Radar and Wireless Communications (MIKON)*, pages 415–418, Vilnius (Lithuania).

Durgin, G. D. and Rappaport, T. S. (1999). Effects of Multipath Angular Spread on the Spatial Cross-Correlation of Received Voltage Envelopes. In *IEEE Vehicular Technology Conference (VTC)*, pages 996–1000, Houston, Texas, USA.

Haykin, S. S. (2002). *Adaptive Filter Theory.* Prentice Hall, New Jersey.

Kühn, V. (2006). *Wireless Communications over MIMO Channels – Applications to CDMA and Multiple Antenna Systems.* Wiley, Chichester.

McKay, M. R. and Collings, I. B. (2005). Capacity and Performance of MIMO-BICM with Zero-Forcing Receivers. *IEEE Transactions on Communications*, 53(1):74– 83.

Mueller-Weinfurtner, S. H. (2002). Coding Approaches for Multiple Antenna Transmission in Fast Fading and OFDM. *IEEE Transactions on Signal Processing*, 50(10):2442–2450.

Narasimhan, R. (2003). Spatial Multiplexing with Transmit Antenna and Constellation Selection for Correlated MIMO Fading Channels. *IEEE Transactions on Signal Processing*, 51(11):28292838.

Oestges, C. (2006). Validity of the Kronocker Model for MIMO Correlated Channels. In *Vehicular Technology Conference*, volume 6, pages 2818–2822, Melbourne.

Zelst, A. v. and Hammerschmidt, J. S. (2002). A Single Coefficient Spatial Correlation Model for Multiple-Input Multiple-Output (MIMO) Radio Channels. In *27th General Assembly of the International Union of Radio Science*, Maastricht.

Zheng, L. and Tse, D. N. T. (2003). Diversity and Multiplexing: A Fundamental Tradeoff in Multiple-Antenna Channels. *IEEE Transactions on Information Theory*, 49(5):1073–1096.

Zhou, Z., Vucetic, B., Dohler, M., and Li, Y. (2005). MIMO Systems with Adaptive Modulation. *IEEE Transactions on Vehicular Technology*, 54(5):1073–1096.