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MIMO LINK MODELING FOR SYSTEM LEVEL SIMULATIONS

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ABSTRACT

MIMO (Multiple Input – Multiple output) systems apply multiple antennas to increase signal to noise ratio (SNR), reduce interference and/or send multiple streams simultaneously over a single channel. Besides increasing the data rate of the physical layer (PHY), benefits can be achieved with cross-layer optimization approach exploiting the layered structure of the channel.

In this paper we focus on MIMO schemes with multiplexing and/or diversity gain and present a link model for system level simulations. The model maps total SNR to achievable link level throughput, both per spatial subchannel and cumulative. The model can be combined with an arbitrary coding and modulation scheme and is abstract enough to be applied to any system protocol, fulfilling the given conditions about channel propagation characteristics.

I. INTRODUCTION

Coarse classification recognizes two types of MIMO techniques based on the propagation channel properties, i.e. on the structure of the spatial correlation matrix at the receiver's antenna array. In case of high correlation of the received signal different beamforming algorithms are applied, and in the case of low correlation of received signal - diversity and multiplexing approaches [1]. There are a lot of derived schemes, whose performance and applicability highly depend on the amount of channel knowledge present at the transmitter and at the receiver. For some of them we give a brief description.

Beamforming techniques are used for steering beams towards the intended user. The benefits are twofold: transmit power is not wasted in other directions, and interference is reduced. Beamforming algorithms assume the channel knowledge at the transmitter. It can be either long-term (only the statistics), or the instantaneous channel knowledge. Some of the beamforming methods, such as conventional beamformer, null-steering and optimal beamformer are described in [10].

In the focus of this work are MIMO methods in narrower sense, namely spatial multiplexing and diversity schemes. In rich scattering environments where the signal at the receiver's antenna elements is not correlated, the receiver can take benefit from the fact that the signals propagating between different transmit – receive antenna pairs undergo different and independent paths. Assuming n antennas at both transmitter and receiver and with some simplifications, MIMO can be described in the following way: the receiver has to solve n equations (n received signals on n receiver's antenna elements), with n variables (n signals), having the knowledge of all the coefficients in n equations ($n \times n$ channel gains from each transmit antenna to each receive antenna) [11]. The necessity for independent fading becomes now clear: non-negligible correlation of the received signal will make the set of equations linearly dependent, thus the system will not have a unique solution.

The benefit from using spatial dimension in MIMO methods in narrower sense can be gained either by simultaneous transmission of multiple streams (spatial multiplexing – MUX), which increases throughput, or exploiting diversity (spatial diversity – DIV) from transmitter and/or from receiver for higher reliability.

In [1] and [11], the authors give a comprehensive overview of different MIMO transmission techniques and discuss their potential in different scenarios, by deriving the channel capacity. In [13], different signal processing techniques are presented, concerning predistortion at the transmitter and equalization at the receiver.

The focus of this work is to investigate the potential benefits of MIMO, using cross-layer protocol design. As a framework for the research in this area, we present a MIMO link model for system level simulations and investigate the *maximum throughput* which can be achieved under the given conditions. Unlike other MIMO channel models, such as the ones given in [12], the model does not incorporate detailed propagation conditions, (e.g. angles of arrival and departure and their spread). We assume rich scattering environment, which results in independent Rayleigh fading between different antenna pairs. If the environment has little scattering and/or the fading is slow, the approaches presented in [14], [18] can be used to induce random fading.

It is worth noting that the presented model, directly calculating the packet error rate (PER) between each transmit-receive antenna pair, or alternatively the link throughput, is very beneficial for system level simulations, due to its low computational complexity.

This paper is organized as follows: section II gives description of the link model and MIMO schemes in narrower sense. In section III we give the theoretical background for calculating the throughput for MIMO links with different antenna constellations. We selected a set of illustrative MIMO schemes for evaluation with the link model and simulation results are presented and analyzed in section IV. In Section V conclusions are drawn and an outlook to future work is provided.

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II. Spatial Multiplexing vs. Spatial Diversity

In MUX schemes, multiple streams are transmitted simultaneously, each using one dedicated antenna. This increases the throughput with the factor equal to the number of streams being transmitted. In DIV schemes, multiple antennas are used in a different way: for the basic DIV scheme transmitter has only one antenna. The receiver with multiple antennas has multiple copies of the transmitted signal and with an appropriate signal processing algorithm extracts significantly higher SNR. This value is referred to as post-processing per-stream SNR. In this paper, we assume that the receiver is using zero-forcing (ZF) algorithm. DIV schemes do not increase the throughput, but the reliability of the transmission.

In the schemes combining MUX and DIV, more transmit antennas are active, but the receiver, as in DIV schemes, still has more antennas than the number of streams: multiplexing is present, but the receiver gets more information about the transmitted signal than in the pure MUX case.

If the post-processing SNR for a stream from certain antenna is not higher than a certain threshold, it is better not to activate transmission from this antenna, but to use instead more transmit power for the antennas whose channel is in good condition. This leads to selection diversity (SDIV). Based on post-processing per-stream SNR values, the best, or a subset of good antennas, which should be used for the transmission, is identified and this information is fed back to the transmitter [7], [16]. Selection diversity with lower multiplexing factor may lead to higher throughput than pure multiplexing schemes with higher multiplexing factor, because of the smart transmit power distribution among antennas.

In all of the described schemes, MIMO channel is divided into a set of independent Single Input – Single Output (SISO) channels, where each SISO channel is used to transmit a single stream, which can be received with the according post-processing SNR.

III. Throughput Calculation For MIMO Links

A. Post-processing per-stream SNR with ZF Receiver

In this section, the post-processing per-stream SNR calculation is presented. We consider a link between two stations. Number of antennas at the transmitting station is M_t and at the receiving station is M_r; the number of receive antennas is not smaller than the number of transmit antennas ($M_t \leq M_r$). Each active transmit antenna transmits a single data stream which is encoded and modulated independently from other streams of other antennas. All the active transmit antennas are using the equal fragment of the total transmit power. It is assumed that the transmitter does not have any channel knowledge, while the receiver has perfect channel knowledge, obtained using pilot channels and applying the ZF algorithm.

We use the following signal model for the MIMO link:

$$y = \sqrt{\frac{E}{M_t}} Hs + n \tag{1}$$

where y is $M_r \times 1$ received signal vector, E is the total received energy, H is $M_r \times M_t$ channel transfer function matrix, s is $M_t \times 1$ transmitted symbol vector, and n is $M_r \times 1$ zero mean circularly symmetric complex Gaussian noise vector at the receiver with variance N_0 in each dimension. The ZF receiver applies the equalizer matrix G_{ZF} to the received vector y:

$$G_{ZF} = \sqrt{\frac{M_t}{E}} H^{\dagger} \tag{2}$$

where $H^{\dagger}$ stands for pseudoinverse matrix of matrix H. Consequently, the output of the ZF receiver is given by:

$$z = s + \sqrt{\frac{M_t}{E}} H^{\dagger} n \tag{3}$$

and the post-processing SNR on stream k is given by [6]:

$$SNR_k = \frac{E}{M_t N_0} \frac{1}{[H^H H]^{-1}_{k,k}} \tag{4}$$

where $H_{k,k}$ stands for the (k, k) entry of matrix H.

We use block fading Gaussian matrix channel model, where the channel is described by a matrix, whose elements are independently and identically distributed circularly symmetric complex Gaussian random variables. The matrix is assumed constant over the duration of a packet, changes though for each channel use and is uncorrelated in time. This is a realistic model under the following conditions:

- the transmission bandwidth is much less than the coherence frequency of the channel (frequency flat channel),
- the antenna spacing is larger than the coherence distance (decorrelated antennas),
- the packets are separated by at least the coherence time of the channel (channel matrix values for each channel use are uncorrelated in time),
- packet length is not longer than the channel coherence time (channel matrix is constant during the transmission of a packet), and
- sufficient scattering is present (independent elements in channel matrix)[2],

These conditions are in most of the cases met in indoor environments.

It has been proved in [3] and [4] that, if channel matrix elements are independently and identically distributed circularly symmetric complex Gaussian random variables, post-processing SNR on stream k is a χ^2-distributed random variable, with $2(M_r-M_t+1)$ degrees of freedom.

B. PER Calculation

We use the method described in [5] for PER calculation. PER depends, among other parameters, on the received SNR. With certain antenna constellation and MIMO schemes, post-processing per-stream SNR can be significantly higher than that of the SISO channel. For this reason, besides the PHY modes defined in the 802.11a standard [9], two additional ones, with higher constellations are analyzed.

PHY modes are presented in Table 1. Both new PHY modes use 256 QAM and binary convolutional encoding with constraint length *K=7*: one with code rate *R=2/3*, and the other with *R=3/4*.

Table 1. PHY Modes

PHY mode m	Code rate	Modulation	Number of data bits per symbol
1	1/2	BPSK	0.5
2	3/4	BPSK	0.75
3	1/2	QPSK	1
4	3/4	QPSK	1.5
5	1/2	16 QAM	2
6	3/4	16 QAM	3
7	2/3	64 QAM	4
8	3/4	64 QAM	4.5
9 (new)	2/3	256 QAM	5.33
10 (new)	3/4	256 QAM	6

The last column in Table 1 contains the number of data bits per symbol for the given PHY mode and will be used in following sections for the evaluation and comparison between different MIMO schemes. Assuming the Nyquist pulse shaping filter with bandwidth $B=1/T_s$, where T_s is the symbol duration, this value corresponds to the PHY mode spectral efficiency.

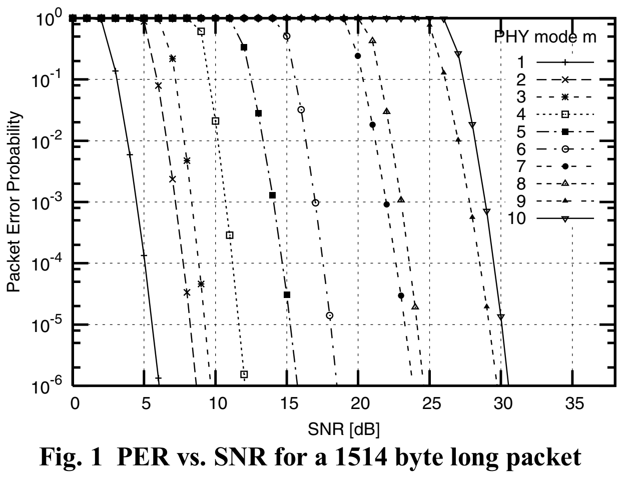

Fig. 1 PER vs. SNR for a 1514 byte long packet

Fig. 1 gives the PER vs. SNR for the used PHY modes, assuming the packet length of 1514 byte, which is the Ethernet maximum frame size. Having higher constellation size and code rates, two new PHY modes require higher SNR for the same PER (for the SNR interval of interest, in average 5-6 dB more than 64 QAM with *R=3/4*), which in the average SISO scenarios is rare, but often reached when using MIMO.

C. Throughput Calculation

For evaluation of the throughput, we calculate the average number of correctly received data bits normalized to symbol duration, using the following formula:

$$N_{\text{data bits / symbol time}} = \sum_{i=0}^{n-1} \left(1 - PER_i\right) \times R_i \times \log_2 M_i \quad (5)$$

where n is the number of independent streams sent, R is the code rate, and M the modulation constellation size of the used PHY mode. Number of data bits per symbol per PHY mode in Table 1 is the theoretical maximum value (for PER=0) for the schemes with one spatial stream. When spatial multiplexing is applied, the throughput for the whole link is the sum over all spatial streams. It is worth noting that this value is related to spectral efficiency, but in contrast takes into account only *correctly received data bits*, without the redundant bits originating from error correction coding, and bits from erroneously received packets.

IV. SIMULATION RESULTS

In this section, simulation results of the MIMO link model are presented and analyzed. We selected the following schemes: SISO, DIV - 1×2 (1 transmit antenna, 2 receive antennas), SDIV - 2×2, MUX - 2×2, MUX - 3×4 and MUX - 4×4. Fixed total transmit power is assumed: transmit power for an antenna element is equal to the total transmit power divided with the number of spatial streams.

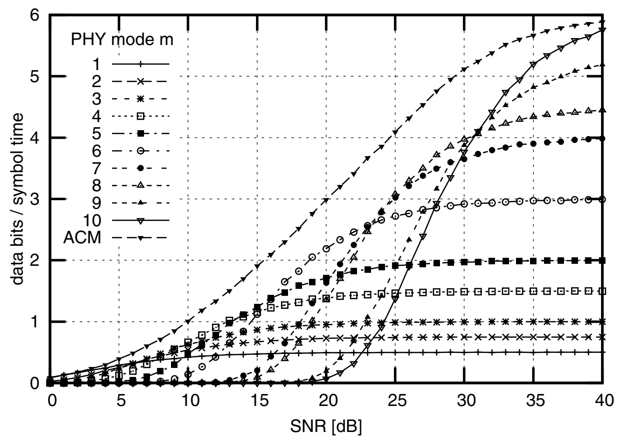

Fig. 2 Number of received data bits normalized to symbol duration for SISO 1×1

Fig. 2-Fig. 7 give numbers of received data bits normalized to symbol duration for the case of SISO 1×1, DIV 1×2, SDIV - 2×2, MUX - 2×2, MUX - 4×4 and MUX - 3×4 scheme, respectively. Simulations are done for all the PHY modes and for adaptive coding and modulation (ACM). The SNR value in the abscissa is calculated as total transmit power reduced

by pathloss, over noise at the receiver; we refer to this value as pre-processing SNR.

Fig. 2 illustrates the performance of the SISO transmission, and we will use it further for the reference values. Having only one spatial stream, the maximum number of data bits normalized to symbol duration (in the absence of packet errors) for each PHY mode corresponds to the value from the last column of Table 1. For ACM it is equal to that of the highest PHY mode – 6.

Fig. 3 corresponds to DIV 1×2 scheme. Theoretical maximum spectral efficiency for this diversity scheme is not higher than that of SISO scheme, since again only one spatial stream is present, but there is still difference in the performance. With the same pre-processing SNR, higher post-processing SNR is extracted. This is due to signal processing of the two avilable copies of the transmitted symbols at the receiver. Reliability of the transmission is increased: for the same pre-processing SNR and with fixed PHY modes, PER values are significantly lower than those of SISO. This translates to higher throughputs (e.g. PHY 6, SNR = 15 dB: SISO – 1.2 data bits per symbol time; DIV 1×2 – 2.3 data bits per symbol time). For the same reason, ACM applies higher PHY modes for lower pre-processing SNR values.

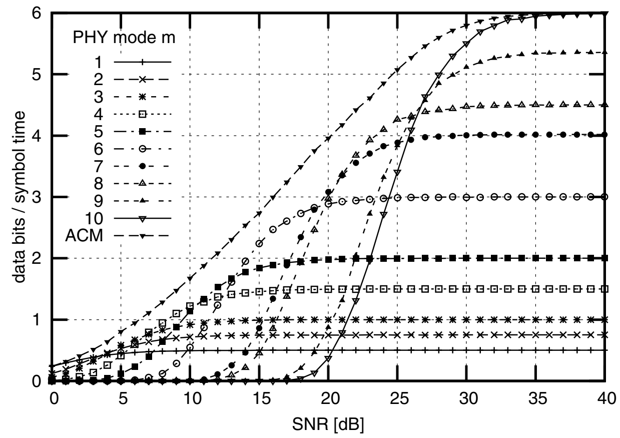

Fig. 3 Number of received data bits normalized to symbol duration for DIV 1×2

It should be noted, that the previous scheme does not require any change at the transmitter compared to SISO case; furthermore, the transmitter is not aware of the receiver having more antennas. For the following schemes, some form of information exchange between the receiver and the transmitter is necessary, to determine which antennas will be used.

As the third scheme with only one spatial stream, the performance of SDIV 2×2 is presented in Fig. 4. Since diversity sources are now both the receiver and the transmitter, reliability is further increased for fixed PHY modes (e.g. PHY 6, SNR = 15 dB: SISO – 1.2 data bits per symbol time; DIV 1×2 – 2.3 data bits per symbol time; SDIV 2×2 – 2.8 data bits per symbol time), and ACM achieves higher throughput (pre-processing SNR when saturation is reached: SISO – more than 40 dB; DIV 1×2 – 33 dB; SDIV 2×2 – 29 dB).

Fig. 5-Fig. 7 present numbers of data bits normalized to symbol duration for MUX 2×2, MUX 4×4 and MUX 3×4.

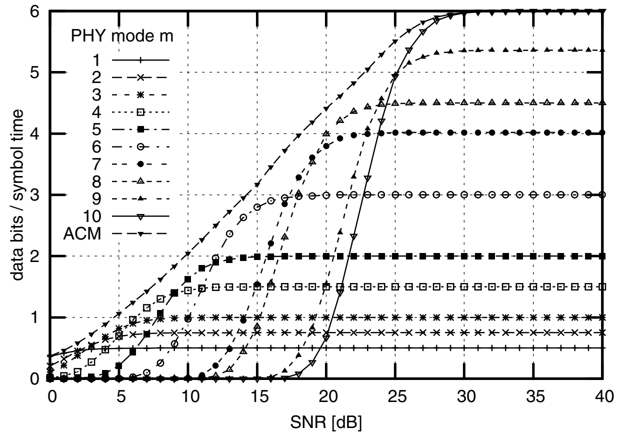

Fig. 4 Number of received data bits normalized to symbol duration for SDIV 2×2

In case of spatial multiplexing schemes more antennas are transmitting simultaneously independent streams. ACM is also done independently for each stream. Since now more spatial streams are present, number of data bits *per symbol duration* will be equal to the sum of the number of data bits *per symbol* from all spatial streams. Accordingly, the theoretical maximum received data bits per symbol time (for PER=0) for PHY 10, for MUX 2×2, MUX 4×4 and MUX 3×4, are 12, 24 and 18, respectively.

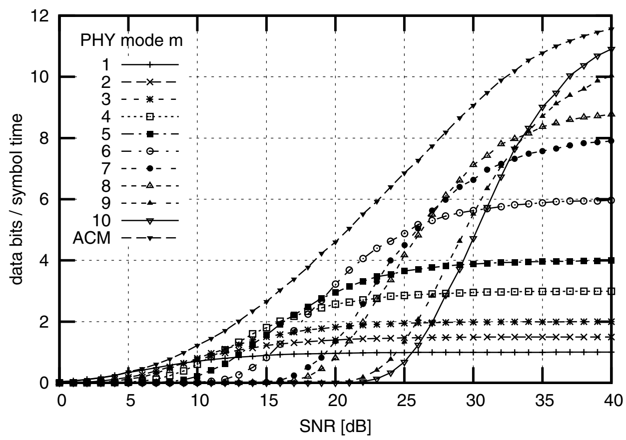

Fig. 5 Number of received data bits normalized to symbol duration for MUX 2×2

For comparison, total transmit power is kept fixed for all the schemes. Each antenna uses only a fraction of the power used for an antenna in SISO case, thus performance of a single spatial stream compared to the SISO stream will be worse. However, the overall performance for the link is still better.

MUX 2×2 and MUX 4×4 are pure multiplexing schemes;

on the other hand, MUX 3×4, having one antenna more at the receiver, exploits receive diversity. Even though MUX 4×4 gives better performance than the other two schemes, for high pre-processing SNR values, it still does not reach the theoretical maximum performance at 40 dB.

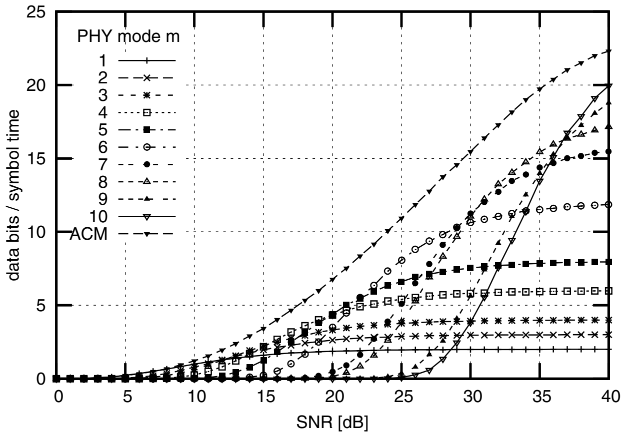

Fig. 6 Number of received data bits normalized to symbol duration for MUX 4×4

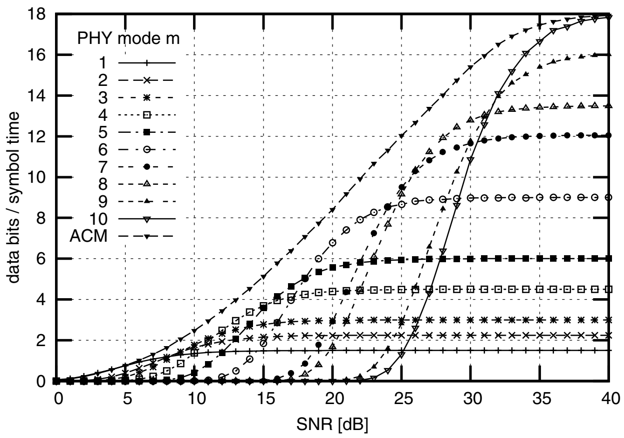

Fig. 7 Number of received data bits normalized to symbol duration for MUX 3×4

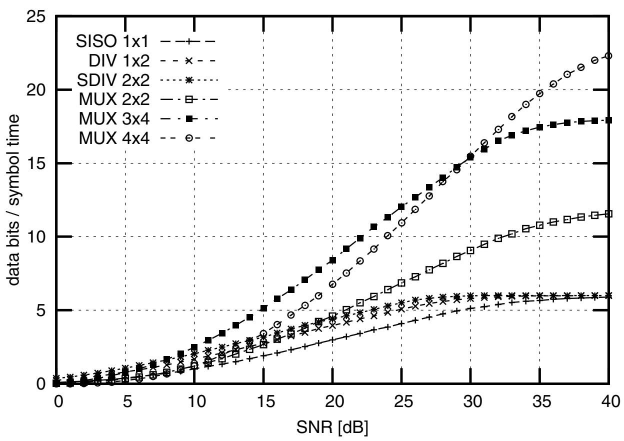

Fig. 8 Number of received data bits normalized to symbol duration for different MIMO schemes with ACM

Fig. 8 gives comparison of ACM curves for all the analyzed schemes. MUX 3×4 gives the best performance in the area of low and moderate SNR. The maximum throughput (6 data bits per symbol time) that can be reached with SISO for more than 35 dB, is reached with MUX 3×4 at 16 dB. For high SNR values, over 30 dB, MUX 4×4 gives better performance; the reason for this is that MUX 3×4 goes into the saturation with 18 data bits per symbol time, while the throughput for MUX 4×4 continues to grow with SNR. The lack of diversity is compensated by multiple spatial streams.

Fig. 9 illustrates the average number of correctly received data bits normalized to symbol time *per spatial channel* which is equal to the average number of data bits per symbol. This will give more insight into the structure of the channel and the origin of performance improvements. The selected schemes in the order from best to worst performance are: SDIV 2×2, DIV 1×2, SISO, MUX 3×4 (for SNR values higher than 30 dB performs better than SISO), MUX 2×2 and MUX 4×4.

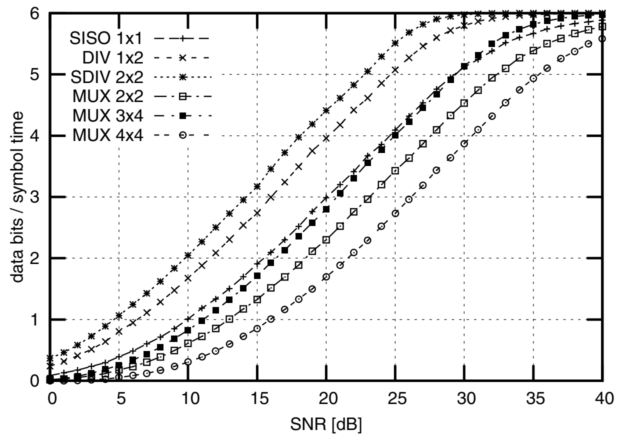

Fig. 9 Number of received data bits per used spatial subchannel normalized to symbol duration for different MIMO schemes with ACM

SDIV 2×2 has the highest diversity gain and therefore has the best performance. The receiver chooses the better out of two antennas at the transmitter to be used for data transmission. In the case of DIV 1×2, the gain arises from receive diversity. MUX 3×4 also has diversity gain, using three out of four spatial channels. SISO, MUX 2×2 and MUX 4×4 schemes do not have any diversity gain and the difference in performance comes from the different power per stream used: since the total transmit power is fixed, for each stream in MUX 2×2 half of the power in SISO case is used, and in MUX 4×4 a quarter.

On stream level DIV schemes are superior to MUX schemes. However, MUX still has better cumulative performance due to multiplexing gain, at least for high SNR values. In moderate SNR interval, diversity significantly improves performance. MUX 3×4 clearly performs superior compared to the other schemes, having a good balance between multiplexing and diversity gain.

V. Summary And Conclusions

In this paper we presented MIMO link model for system level simulations. The simulation results for different MIMO schemes in the single-user case gave both an illustration and validation of the model, as well as an insight into the fundamental trade-off between multiplexing and diversity gain.

The model, as presented, is not limited to any specific system (if the propagation environment complies with the given conditions). It should be noted here, that the efficiency of the transmission is given in number of data bits normalized to symbol time. Protocol overhead is not introduced to keep the generality of the model.

Future work includes extension of the MAC protocol for MC-CDMA based IEEE 802.11 Wireless LAN [8] with MIMO awareness.

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