On Performance of MIMO Link Adaptation in the Presence of Channel Uncertainty

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***Abstract*—In this paper, link level adaptation algorithms in a system applying spatial multiplexing in the presence of channel uncertainty are considered. The first part of this paper deals with the impact of accuracy of the channel knowledge on the post-processing Signal-to-Noise Ratio (SNR) of transmitted multiple streams. This is evaluated by means of correlation coefficient between post-processing SNR values corresponding to the estimated and used channel matrix.**

In the second part of this paper, two link adaptation algorithms are introduced: the first algorithm adapts the modulation and coding scheme to the post-processing SNR level, whereas the second one searches for the optimum MIMO scheme (antenna selection) and does afterwards the adaptation of modulation and coding as well. Algorithms' performance is evaluated assuming perfect channel knowledge and in the presence of channel uncertainty. The two algorithms show different gains when the channel knowledge is accurate, but also different sensitivity to channel knowledge imperfections.

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***Keywords*: MIMO, spatial multiplexing, link adaptation, antenna selection, link capacity, channel uncertainty**

I. Introduction

Multiple Input-Multiple Output (MIMO) is a wide set of multiple antenna technologies that can significantly increase the capacity of wireless networks, without additional bandwidth or increased transmission power. They are widely recognized as technologies essential for meeting, at relatively low cost, ever growing network requirements, such as higher data rate, high mobility, Quality of Service (QoS) support, higher security, support for diversity and plurality of devices and services, etc.

Based on the optimization criterion set by the applied algorithm, MIMO technologies can be divided into three classes: Spatial Multiplexing (SMUX) - methods to increase the link/system capacity, Space-Time Coding (STC) - methods to increase the robustness of the communication link, and beamforming and Space Division Multiple Access (SDMA) - methods to reduce co-channel interference.

MIMO based Physical layer (PHY) provides the transmission channel with a layered structure that gives another degree of freedom in link adaptation and scheduling transmissions. Thus, a cross-layer approach that provides efficient management of the channels spatial layers, can significantly increase the networks performance on both link and system level. Cross-layer design gets another dimension compared to conventional, single-antenna systems. Therefore, e.g. with a properly designed link adaptation algorithm and fine-grained resource allocation, there is a high potential for boosting the network performance. These methods, however, require some form of Channel State Information (CSI) at both transmitter and receiver, and their performance also depends of the accuracy of the CSI.

A. Related Work

Depending on the particular MIMO scheme, the performance on the PHY, as well as the scheduling methods highly depend on the accuracy of the estimated channel. The impact of the channel uncertainty of the channel capacity was investigated in [1]. The authors in [2] investigated the required channel feedback frequency in different systems, pointing out that the coherence time is not the only crucial parameter, but also other system configuration parameters such as number of antennas and modulation scheme. Antenna selection and the different optimization criteria are presented in [3], [4], [5]. In [5] the authors also investigate the error rate performance with zero-delay, zero-error feedback, thus not regarding the impact of channel uncertainty.

In this work link adaptation is analyzed for a spatial multiplexing system. Different degrees of freedom in link adaptation are investigated. Link level performance evaluation is done by Monte-Carlo simulations, assuming different accuracy of channel knowledge.

This paper has the following structure: Section II contains the description of the receiver algorithm and introduces the post-processing SNR that characterizes the stream SNR level. In Section III modeling of channel uncertainty is presented, and its impact to estimated post-processing SNR is investigated in Section IV. The remaining analysis is done on the system described in Section V. Link adaptation with a fixed MIMO scheme and spatially adaptive MIMO scheme are investigated in Section VI and in Section VII, respectively. The impact of channel uncertainty on both adaptation algorithms is analyzed in Section VIII. Finally, conclusions and outlook to future work are give in Section IX.

II. Post-Processing SNR in SMUX Schemes

This paper is primarily concerned with SMUX schemes. In SMUX schemes, multiple streams are transmitted simultaneously, each one using a dedicated transmit antenna. The receiver also has multiple antennas that receive a signal that is a sum of the transmitted signals propagating different paths. Provided rich multipath scattering, by applying an appropriate

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signal processing algorithm the original symbols are separated at the receiver. Thereby, the throughput increases with a factor equal to the number of transmitted streams.

In this work the receiver applies the MMSE algorithm for separating multiple streams, and afterwards performs detection independently on each stream. The channel transfer functions between each transmit/receive antenna pair is assumed to be independent and identically distributed zero-mean circularly symmetric complex Gaussian random variable with unity variance.

The following signal model is used for the link between M_t transmit and M_r receive antennas:

$$\mathbf{y} = \sqrt{\frac{E}{M_t}}\mathbf{Hs} + \mathbf{n}, \quad (1)$$

where E is the total received energy, $\mathbf{y}$ is the $M_r \times 1$ received signal vector, $\mathbf{H}$ is the $M_r \times M_t$ channel transfer function matrix, $\mathbf{s}$ is the $M_t \times 1$ transmitted symbol vector, $\mathbf{n}$ is the $M_r \times 1$ noise vector at the receiver with variance N_0.

The MMSE receiver minimizes the total error (coming from multiple stream interference and noise), by applying the filter matrix with the following form [6]:

$$\mathbf{G_{MMSE}} = \sqrt{\frac{M_t}{E}}\left(\mathbf{H}^H\mathbf{H} + \frac{M_t N_0}{E}\mathbf{I_{M_t}}\right)^{-1}\mathbf{H}^H. \quad (2)$$

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

$$\eta_k = \frac{1}{\left[\left(\frac{E}{M_t N_0}\mathbf{H}^H\mathbf{H} + \mathbf{I_{M_t}}\right)^{-1}\right]_{k,k}} - 1. \quad (3)$$

III. Link Adaptation and CSI Uncertainty

The fundamental condition for applying link adaptation methods is the presence of some form of the channel quality measurement at the transmitter. The transmitter can obtain CSI either by estimating the forward channel and assuming the channel reciprocity, or by requesting the channel feedback from the receiver. In both cases, there is a certain error between the estimated channel and the channel at the time of the transmission. The duration between the channel estimation and the actual channel usage will impact the accuracy in both cases, whereas in the former case the differences between the forward and reverse channel introduce additional error. There are also other impacts, such as measurement error.

A. *Channel Time Correlation Function*

In mobile environment, the channel impulse response changes with time. A widely accepted scattering model to describe the signal received by a moving vehicle was introduced by Clark [7]. In this model, the transmitted signal is distorted by three effects:

- a Rayleigh distributed signal attenuation,
- a phase shift uniformly distributed in the range [0,2π] that is independent of the attenuation,
- a Doppler frequency offset.

In the case of an uniform distribution of the multipath angle of arrival between 0 and 2π, the Doppler spectrum is U-shaped and it can be proved that the channel time correlation function has the following expression [8], [9]:

$$R(\Delta t) = J_0(kV\Delta t), \quad (4)$$

where $J_0(\cdot)$ is is the zero-order Bessel function of the first kind.

The channel time correlation function at 5 GHz carrier frequency is plotted in Fig. 1 for 5 km/h and 100 km/h terminal speed. As a zero-order Bessel function of the first kind, the channel time correlation function is an oscillatory function, hence not invertible. As the following analysis is based on the performance depending on the magnitude of the channel time correlation function, it will correspond to time T when the function takes the given value for the first time.

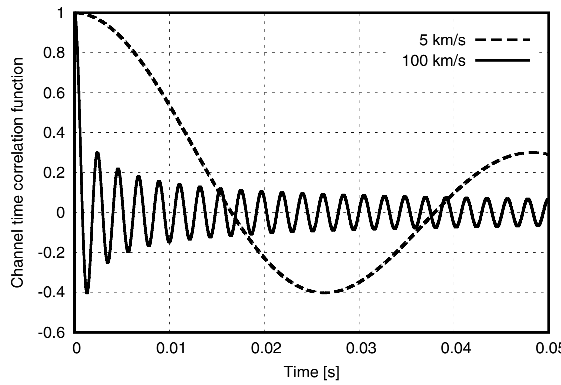


Fig. 1. Channel time correlation function at 5 GHz carrier frequency for 5 km/h and 100 km/h terminal speed

IV. Post-Processing SNR Time Correlation

In the focus of this section is the correlation coefficient between the post-processing SNR values corresponding to the channel at the time of estimation and at the time it is used. The analysis is done in the presence of channel uncertainty under different SNR levels and for different antenna configurations.

The estimation of the channel matrix H is performed at $t = 0$, the transmitter receives the feedback and transmits data at $t = T$. The transmitter has the knowledge of the post-processing SNR values that correspond to the channel matrix $H(0)$, which differ from the ones corresponding to the channel matrix $H(T)$. The time $\Delta t = T$ that elapses determines the correlation level between the channel matrices $H(0)$ and $H(T)$, and inherently the correlation between the achievable post-processing SNR values.

In Fig. 2 the dependency of post-processing SNR correlation coefficient on the channel time correlation and SNR level is illustrated for the 4×4 antenna link. The post-processing SNR correlation coefficient grows rather slow by the channel time correlation level, which underlines the importance of the accurate channel information for performing link adaptation in an optimal way. It can also be seen that the correlation is higher in the low SNR region.

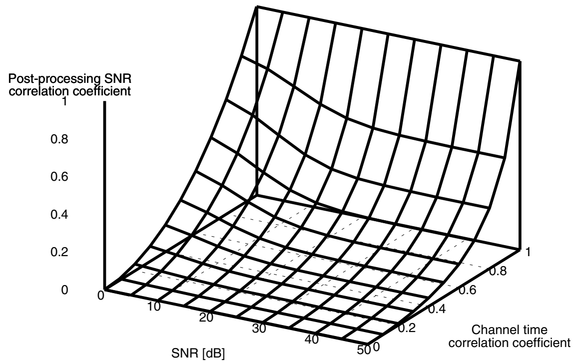
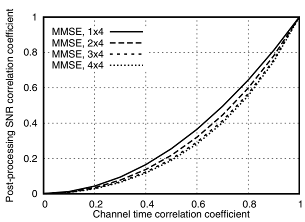
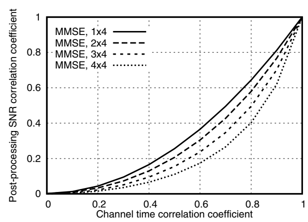


Fig. 2. Post-processing SNR correlation coefficient depending on the channel time correlation coefficient and SNR level for 4×4 antenna link

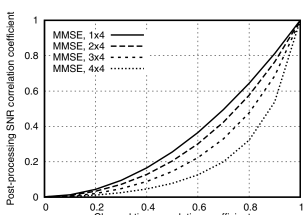
For a comparative performace analysis of links with different number of antenna streams, in Fig. 3 the post-processing SNR correlation vs. channel matrix correlation is plotted at 5 dB, 15 dB and 40 dB SNR, for 1×4, 2×4, 3×4 and 4×4 antenna links.



(a) SNR= 5 dB



(b) SNR= 15 dB



(c) SNR= 40 dB

Fig. 3. Post-processing SNR correlation coefficient depending on the channel time correlation coefficient at different SNR levels for 1×4, 2×4, 3×4 and 4×4 links

Several observation can be made: first, the post-processing SNR correlation coefficient over an 1×4 antenna link practically does not depend on SNR. The 1×4 antenna link achieves the highest post-processing SNR correlation at all input SNR levels, since with diversity the channel can be estimated with higher accuracy. With each additional transmit antenna i.e. spatial stream, the post-processing SNR correlation degrades, so finally the 4×4 antenna link has the worst performance. Also, the post-processing SNR correlation degrades with the increasing SNR of the receive signal.

V. System Model

In the following, link adaptation for the link established by two stations with multiple antennas is analyzed. Data transfer is done following Multi-User - Distributed Coordination Function (MU-DCF) protocol introduced in [10]. MU-DCF is an IEEE 802.11 based MAC protocol with support for multiple antennas. The channel parameters, as well as Interframe Spaces (IFSs) are taken from the IEEE 802.11a standard [11], and given in Table I.

After the transmitter sends the MIMO frame, the receiver filters the received signal on different antennas, and detects the symbols on each stream. The correctly received packets are marked in the Acknowledgment (ACK) frame that is sent back to the transmitter using a single antenna and QPSK $1/2$ PHY (12 Mb/s). The ACK frame is also used to piggy-back the CSI to be used for the following transmission; alternatively, the ACK frame contains the channel estimation sequence if the transmitter may assume a reciprocal channel.

TABLE I
System Parameters

Parameter	Value
Channel Bandwidth	20 MHz @ 5.2 GHz
Number of Subcarriers	48 Data + 4 Pilot
Slot duration (σ)	9 μs
SIFS/DIFS/EIFS	16 μs / 34 μs / 94 μs
CW_{min}	15
Data frame length	1024 byte

VI. Adaptive Modulation and Coding (AMC) with Fixed MIMO scheme

AMC for a MIMO link is described in Algorithm 1. The algorithm operates as conventional AMC algorithm, with the difference that it uses post-processing SNR values as input parameters to assign the PHY mode for each transmit antenna.

In case that the PHY mode can be adapted to the post-processing SNR level on each stream so that Packet Error Rate (PER) for that SNR does not exceed a predefined threshold, the lowest chosen PHY mode will determine the duration of the MIMO frame transmission. Calculation of PER for particular coding and modulation scheme is given in [12]. From the PHY modes defined in IEEE 802.11a standard [11], only a subset is used: 12 Mb/s (QPSK $1/2$), and its multiples with 2, 3 and 4: 24 Mb/s (16 QAM $1/2$), 36 Mb/s (16 QAM $3/4$) and 48 Mb/s (64 QAM $2/3$). In order to have a fair comparison, all the MIMO frames are built in a way that their length corresponds to the length of a frame transmitted at 12 Mb/s, even if that is not the lowest used PHY mode. Using the described MIMO frame structure, the number of packets transmitted at bitrate r on a certain transmit antenna is $\frac{r}{12\,Mb/s}$.

In Fig. 4, mean data rate vs. SNR using fixed and AMC is presented. Links with 1, 2, 3 and 4 transmit antennas are analyzed with the maximum tolerable PER 10^{-2}. The mean data rate with AMC is plotted with solid lines, whereas the other line styles correspond to fixed PHY modes. One would

Algorithm 1 AMC for a MIMO link

for (each transmit antenna j) **do**
  ppSNR$_j$ = post-processing SNR for antenna j
  Assign the highest PHY mode r_j to antenna j, so that PER $<$ PER$_{max}$
  Schedule $\frac{r_j}{12\,Mb/s}$ packets for transmission from antenna j
end for

expect that the solid line is exactly the envelope of the other ones. However, it can be seen that in all cases the solid line overperforms the fixed PHY mode policy, particularly in the SNR regions where the curves corresponding to neighboring PHY modes intersect.

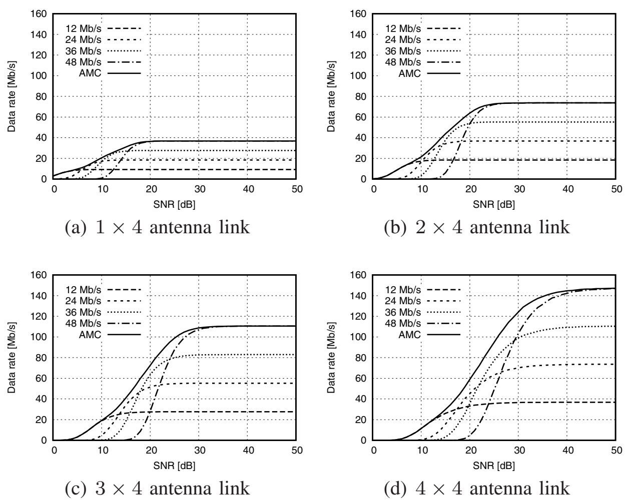


Fig. 4. Mean data rate with fixed and adaptive MCS and varying number of transmit antennas

The reason is the following: when PHY modes are fixed, the same PHY mode is used for each channel realization, independently on the post-processing SNR level. With AMC over a MIMO link, adaptation is done over the post-processing SNR level of each stream. If the adaptation had been done over the average SNR value, thus the same PHY mode would have been assigned to each transmit antenna, the solid line would have matched the envelope of the mean data rate achieved by fixed PHY mode assignment. It can also be seen that the gain grows with the number of used spatial subchannels; the reason is that the variance of post-processing SNR is higher in pure multiplexing schemes.

The gain compared to the best fixed PHY mode is plotted in Fig. 5 for different maximum tolerable PER values: 10^{-1}, 10^{-3} and 10^{-5}. The first thing that can be noticed is the shape of the curves: there are three peaks, each corresponding to a switching point between two neighboring PHY modes, and they happen at approximately same SNR for different maximum PER. The higher these PHY modes are, the higher is also the gain: it goes over 25 Mb/s at about 29 dB SNR with 10^{-1} maximum tolerable PER.

The shapes of the curves corresponding to different maximum tolerable PER levels are the same, but the exploited capacity gain grows with that level because of less restrictive PHY mode assignment. However, the number of packet errors also grows, thus retransmissions occur that degrade the performance on higher layers.

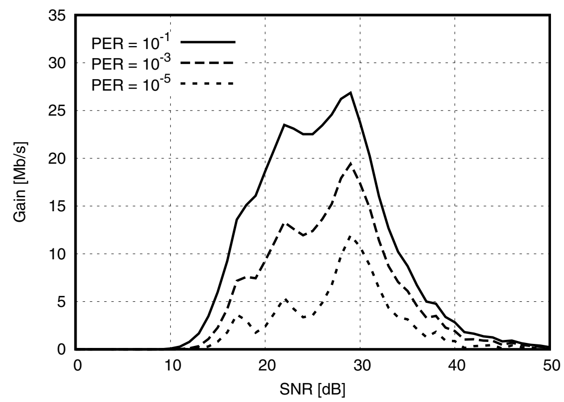


Fig. 5. Capacity gain achieved with AMC for 4×4 antenna link

VII. Spatially Adaptive Modulation and Coding (SAMC)

By relaxing the constraint of a fixed MIMO scheme, the adaptive scheduler applies so called SAMC, that is described in Algorithm 2. The algorithm compares the mean data rate over all possible $\binom{M_t}{k}$ k-combinations of transmit antennas, with $k = 1 \cdots M_t$, and the scheme that achieves the maximum value is selected. This is a combination of antenna selection and AMC.

Algorithm 2 SAMC for a MIMO link

for ($k = 1$, $k <= M_t$, $k++$) **do**
  for (each k-combination $C_{k,c}$ of transmit antennas, $c = 1 \cdots \binom{M_t}{k}$) **do**
    for (each active transmit antenna j) **do**
      ppSNR$_{k,c,j}$ = post-processing SNR for antenna j
      Assign the highest PHY mode $r_{k,c,j}$ to antenna j, so that PER $<$ PER$_{max}$
      Allocate antenna j for transmission of $\frac{r_{k,c,j}}{12\,Mb/s}$ packets
    end for
    Aggregate bitrate for combination $C_{k,c}$ is calculated as $r_{k,c} = \sum_j r_{k,c,j}$
  end for
end for
Choose the combination of antennas C_{n_s,k_s}, $(n_s, k_s) = \arg\max_{k,c}(r_{k,c})$, and the corresponding PHY modes for data transmission

In Fig. 6 a comparison of AMC over 1×4, 2×4, 3×4 and 4×4 antenna links and SAMC algorithm is presented for a maximum tolerable PER of 10^{-2}. In the figure, the mean data rate vs. SNR is presented. The SAMC curve does not closely match the envelope of the AMC curves with fixed MIMO

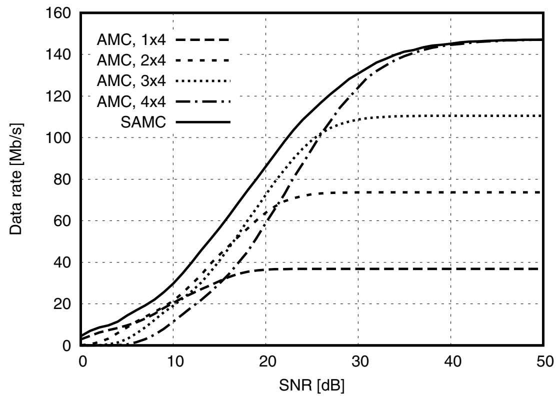


Fig. 6. Mean data rate for SAMC compared to AMC

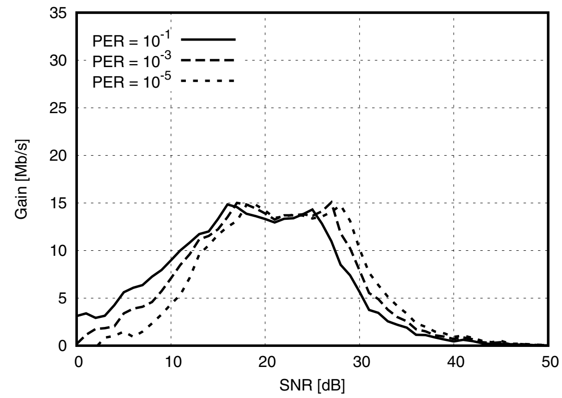


Fig. 8. Capacity gain achieved with SAMC algorithm with different maximum tolerable PER levels

schemes. More flexibility in the link adaptation algorithm brings additional capacity gain.

It is also interesting to compare the link capacities achievable with SAMC using different maximum tolerable PER levels, as presented in Fig. 7. The highest capacity is achieved with the highest tolerable PER: the difference between the curves is more than 20 Mb/s at 20 dB SNR.

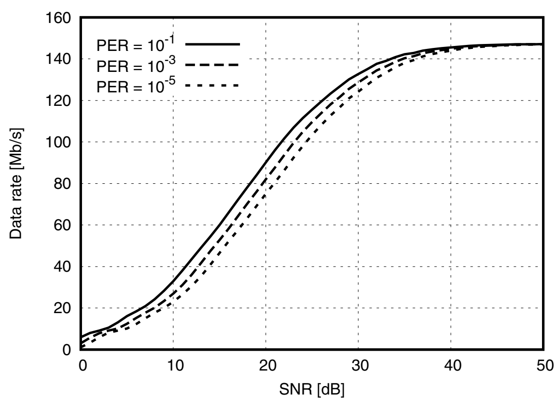


Fig. 7. Mean data rate for SAMC algorithm for different maximum tolerable PER levels

In Fig. 8 capacity gain vs. SNR is plotted for SAMC for different maximum tolerable PER levels. The capacity gain is approximately tha same for all the analyzed cases, but it is shifted in SNR, so that the same gain is achieved earlier in case of higher tolerable PER than in case of lower tolerable PER.

In Fig. 9 the mean number of transmit antennas used with SAMC is plotted. It shows the tendency of using larger number of spatial streams when the SNR value grows. Occasional stagnation intervals occur due to the selected subset of PHY modes: for a certain SNR value using less streams with higher PHY mode yields higher capacity then using more streams with lower PHY mode.

It should also be noted that with AMC, the exact values of achieved gain highly depend on the PHY modes over which

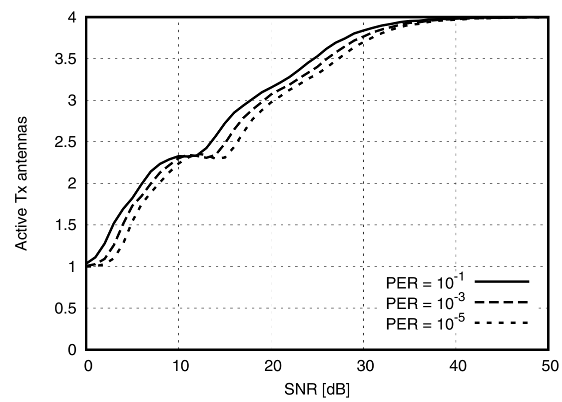


Fig. 9. Mean number of transmit antennas selected by SAMC algorithm

the adaptation is done; however, the conclusions made here still apply in general.

VIII. The Impact of Channel Uncertainty

The accuracy of the channel knowledge impacts the performance of both link adaptation algorithms introduced. In Fig. 10 a comparison of SAMC and AMC is depicted when the used and estimated channel are uncorrelated ($R(T) = 0$).

With an uncorrelated channel, adaptation over the MIMO scheme deteriorates performace, due to "greedy" behavior of the scheduler: e.g. at 23-30 dB SNR, the spatially adaptive scheduler performs worse than the scheduler with the fixed 3×4 antenna scheme. The reason is the following: as depicted in Fig. 9, the spatially adaptive scheduler tends to prefer the 4×4 antenna scheme, that leads to lower average post-processing SNR than the 3×4 antenna scheme. If the AMC algorithm is applied to estimated post-processing SNR values, although they will differ from the actual ones, with 3×4 antenna scheme the probability is higher that the used post-processing SNR level will not drop below the threshold for the chosen PHY mode.

In Fig. 11(a) and Fig. 11(b) the mean data rate with SAMC algorithm under channel uncertainty is presented, for the maximum tolerable PER of 10^{-1} and 10^{-5} respectively.

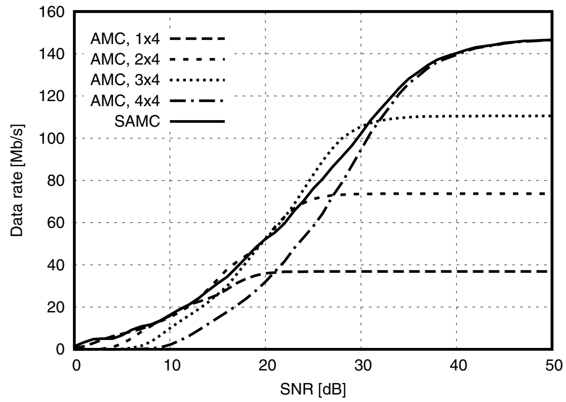


Fig. 10. Comparison of mean data rate with AMC and SAMC with $R(T) = 0$

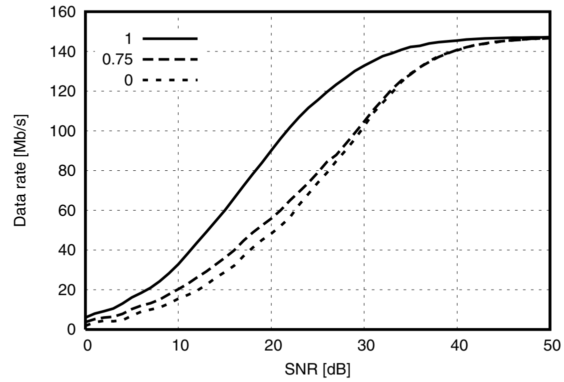
The performance is evaluated for the channel time correlation coefficient values 1.0, 0.75 and 0.0, respectively. It can be seen that the difference among the curves with the higher PER threshold is much larger than in case of lower PER threshold. The reason is that in the former case, the choice of PHY mode is more sensitive to channel estimation: a small decrease of post-processing SNR might push PER to high, whereas in the latter case even if the corresponding post-processing SNR decreases, PER remains low.

IX. Conclusion

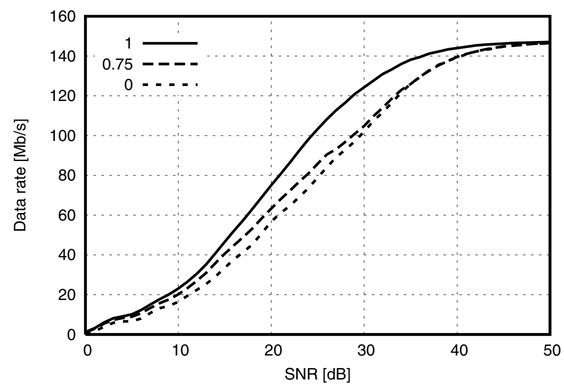
In this paper, the impact of channel uncertainty on the performace of link adaptation in spatial multiplexing system is analyzed. At first, the impact of channel time correlation on the accuracy of the channel metrics (post-processing SNR level) used for the link adaptation is studied. The analysis showed that even for moderate levels of accuracy of post-processing SNR, a high channel time correlation value is needed.

Two link adaptation algorithms are presented, where the first adapts only modulation and coding scheme, whereas the second applies antenna selection as well. The algorithms provide for high capacity gain, but only under reasonable accuracy of the CSI. The analysis of the impact of the maximum tolerable PER on the performance of the link adaptation algorithms showed that with restrictive choice of MIMO, modulation and coding scheme a reduction of the tolerable PER can help to prevent the high gain loss found under channel uncertainty.

Future work will include the system level evaluation of the proposed algorithms in combination with an opportunistic scheduler, with special attention payed to achievable multiuser diversity gains.



(a) Maximum tolerable PER 0.1



(b) Maximum tolerable PER 10^{-5}

Fig. 11. Mean data rate with SAMC for different channel time correlation levels with different maximum tolerable PER

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