Advanced Link Level Techniques for Broadband MIMO Metropolitan Area Networks

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***Abstract*—Within the IST-STRIKE project the increase of the system capacity by means of multiple transmit and multiple receive antenna techniques is investigated. In particular, pre-equalization (downlink) and multi-user detection techniques (uplink) are studied for point-to-multipoint distribution links and compared to advanced space-time processing techniques for point-to-point links. A common simulation platform has been developed in order to ensure a fair comparison of the performance results of the different investigated techniques. In this paper we present the description of the common simulation platform and some of the different investigated techniques along with selected results of the investigations carried out within the IST-STRIKE project. This also includes the MIMO channel model as well as the dynamically reconfigurable simulation chain that hosts the MAC layer library. The latter was developed to investigate the impact of the multiple antenna techniques on the MAC layer.**

***Keywords*—Broadband fixed wireless access (BFWA), HIPERMAN, HIPERLAN/2, OFDM, capacity increase, MTMR techniques, multi-user detection, space-time processing, MIMO channel model, MTMR MAC layer adaptation**

I. Introduction

IST-STRIKE project aims at proposing and demonstrating spectrally efficient broadband access, including both high coverage and QoS (quality of service) guarantee by using interworking networks. The high coverage is brought by a dual standard delivery HIPERMAN (outside) and HIPERLAN/2 (inside) and QoS is assured by appropriate interworking mechanisms between these two broadband standards, where the interworking networks will be provided at the DLC/MAC level. Since the data rates of the studied standards are currently not sufficient considering the envisioned low deployment costs, the increase of the data throughput by means of multiple transmit and multiple receive antenna techniques, MTMR techniques for short, is considered. This approach allows increasing the system throughput and hence to lower the deployment costs by enabling simultaneous parallel data transmissions, e.g. a multiplicity of users can be reached simultaneously. A major objective of the IST-STRIKE project is to demonstrate that the capacity increase in terms of number of simultaneous users in the same time at the same frequencies is possible for both the HIPERMAN and the HIPERLAN/2 standards, thus only with minor modifications of these standards. Furthermore, the impact of this capacity increase on the upper layers, e.g. the MAC/DLC layer, represents one of the main study items. In this respect, the objective is to propose novel DLC strategies that exploit the new user dimension in an optimum way.

In order to achieve the envisioned capacity increase, two different approaches are pursued as a function of the link direction: multi-user detection techniques for the uplink and pre-equalization techniques for the downlink. In parallel, MTMR techniques that increase the capacity for point-to-point communications are studied for comparison. In order to study the different approaches and to compare the results in a fair manner, a common simulation platform has been developed within the IST-STRIKE project. This simulation platform also includes the implementation of a MIMO channel model that can be configured appropriately for typical HIPERMAN and HIPERLAN/2 MTMR transmission channels. Furthermore, the simulation platform was extended to also include a MAC layer library that allows generating and simulating with accurate MAC data rather than with random bit sequences. It is important to note that this approach allows the evaluation of the proposed MAC mechanisms in direct combination with the PHY layer implementation of the advanced MTMR techniques.

The remainder of the paper is organized as follows: in Section II we describe the components of the enhanced link level simulation chain. Section III is dedicated to the evaluation of the multiple access interference whereas performance results of the investigated MTMR techniques are presented in Section IV. Finally, conclusions are summarized in Section V.

II. Enhanced Link Level Simulation Chain

Within the STRIKE project (IST-2001-38354) [1] baseband simulation chains for the PHY layer are developed in order to evaluate the expected performance gains that are made available through introduction of MTMR antenna processing techniques. The STRIKE baseband simulation chains support both, the HIPERMAN standard [2] as well as the HIPERLAN/2 standard. The current versions of these standards, which only provide limited support of MTMR techniques, are implemented in the so-called reference chain. In particular, the implementation of the HIPERMAN standards follows the description of OFDM option of the IEEE standard 802.16a [4] and the HIPERLAN/2 implementation is based on the document [9]. The reference chain serves as the baseline for the performance and complexity comparisons, especially for the MTMR techniques that were integrated into the advanced simulation chains. In particular the advanced simulation chain 1 implements capacity increasing MTMR techniques for point-to-point links, whereas the advanced simulation chain 2 implements MTMR techniques for point-to-multipoint links.

The STRIKE simulation chains are built up of so-called basic building blocks. Each basic building block is characterized through its input and output ports as well as its parameters. The communication between the basic building blocks as well as the scheduling is handled via SystemC [10] mechanism. The implementation of the STRIKE simulation chains follows the methodology outlined in the information note [11], which ensures the efficient re-use and integration of already available source code.

The simulation chains are controlled via a configuration file, which allows the rapid and convenient change of system parameters. The iterative simulation for different values of a specific system parameter, e.g. in order to generate BER curves, is made possible through convenient scripting support.

The STRIKE reference chain is available for public download from the STRIKE web site [1] and both Windows and UNIX/Linux operating systems are supported.

A. MAC Signaling and Adaptive Control Structure

On top of existing blocks of the simulation chain, the standard-compliant HIPERMAN MAC frame structure is implemented [3] [5]. Like this the stream of random bits generated by the block *Source* is substituted by the regular DL sub-frame. It is composed of the DL-preamble followed by the frame control header (FCH) and one or more DL-bursts. DL-burst#1 contains the DL-MAP with its information elements (IEs). The DL-MAP signals the build-up of the DL sub-frame to the receiver, i.e. the subscriber stations (SSs). Each IE of the DL-MAP specifies one DL-burst. Start time and modulation/coding scheme (PHY mode) of the corresponding burst are given so that the receiver is able to decode the received signal. Within one sub-frame different DL-bursts may be scheduled which utilize different PHY modes. Thus, the sender has to code and modulate the bit stream with the given PHY mode and the receiver side has to decode the MAP and adapt its receiving blocks according to the parameters given in the DL-MAP IEs.

Therefore an adaptive control structure is implemented that controls the different blocks of the link level simulation chain. The block *MAC* creates the DL sub-frame, including the DL-MAP, and the control information for the following blocks. On the sender side, the control information is forwarded to the blocks of the chain in parallel to the data stream. Therefore control channels are added to the simulation chain in parallel to the data channels. At the receiver side the DL-MAP has to be decoded first. Having extracted the control information from the IEs, it can be handed back to the receiver blocks. This is done via control channels that connect the block *MAC* directly with the corresponding receiver blocks.

B. MIMO Channel Model

A stochastic model has been used for the frequency selective and correlated MIMO physical channel [6]. The broadband MIMO radio channel without noise, which describes the connection between the user terminal and the BS can be expressed as:

$$\mathbf{H}(\tau)=\sum_{l=1}^{L}\mathbf{H}_l\delta(\tau-\tau_l) \qquad (1)$$

where $\mathbf{H}(\tau)$ is the *MxN* matrix of channel impulse responses and $\mathbf{H}_l$ is the matrix of complex coefficient that describes the linear transformation between the TX and RX antennas array at delay τ_l. This is a simple tap delay line model, where the *L* taps are represented by matrices. The complex transmission coefficients from antenna *n* and antenna *m* are assumed to be zero mean complex Gaussian and have the same average power P_l, depending by the Power Delay Profile PDP. The coefficients are independent from one delay to another. The MIMO channel is assumed to be composed of multiple clustered paths. The spatial correlation is introduced in form of a correlation matrix. This matrix is a Kronecker product of two matrices $\mathbf{R}_{TX}$ and $\mathbf{R}_{RX}$ that characterize the correlation between the antenna elements at the transmitter and the receiver, respectively. The elements of $\mathbf{R}_{TX}$ and $\mathbf{R}_{RX}$ depend on the antenna elements separation, the Power Azimuth Spread (PAS) and the radiation pattern of the antenna elements. See for details about these relationships under the assumption of omnidirectional antennas. The model also incorporates temporal correlation. Both a Jake's Power Doppler Spectrum and a Rounded PDS [8] can be selected.

The implemented frequency selective channels are compliant with the Standford University Interim (SUI) channel models proposed for broadband fixed wireless access systems [8].

C. MTMR Techniques

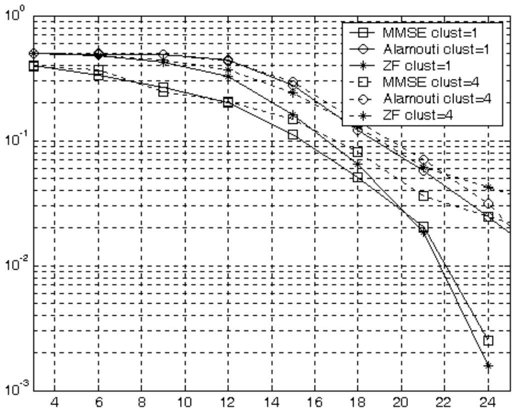
1) Space-time and space-frequency coding

The term space-time coding referrers to digital signal processing techniques for wireless communication systems with multiple transmit antennas. These techniques aim at exploiting the spatial diversity made available through the different communication channels associated with the multiple transmit antennas. The exploitation of spatial diversity is an effective means to alleviate the adverse effects of the wireless transmission channel, like e.g. fading. In general, space-time coding can be classified as being part of the bigger family of transmit diversity techniques. Within this category, space-time coding techniques play a significant role since these techniques do not require any knowledge about the transmission channels, which in turn facilitates the overall system implementation. In this context, space-time coding techniques are of economical interest, especially for cellular communication systems, since such techniques enable the exploitation of transmit diversity for the downlink and receive diversity for the uplink at one side of the communications like, e.g. the base station. At the user terminal one single antenna is sufficient.

In the context of OFDM modulation the domain of space-frequency coding is of special interest. Space-frequency coding basically extends the theory of space-time coding for narrowband flat fading channels to broadband time-variant and frequency-selective channels. The application of classical space-time coding techniques for narrowband flat fading channels to OFDM seems straightforward, since the individual subcarriers can be seen as independently flat fading channels. However, in [13] it was shown that the design criteria for space-frequency codes operating in the space-time- and frequency domain are different from those for classical space-time codes for narrowband fading channels as introduced in [14]. This observation was investigated in some more detail for the Alamouti code, which is the optimum space-time code for two transmit antennas. In [15], a paper that is also published in the WPMC conference proceedings, the authors show that the frequency-selectivity nature of broadband (OFDM) transmission channel requires appropriate receiver processing in order to overcome the performance degradation associated with the standard decoding approach.

2) Spatial multiplexing

Through Spatial Multiplexing (SM) techniques, the multiple antennas are used to boost the data rate for a given reliability of reception (providing multiplexing or degree of freedom gain). They consist in dividing the incoming data into multiple substreams that are transmitted on different antennas [12]. With respect to space-time coding techniques, they are characterized by higher complexity since multiple antennas are required at both ends. However, for fixed wireless access subscriber units, which represent our scenario of interest, size and complexity constraints are more relaxed than for mobile subscriber units, and hence, it make sense considering the application of SM. To un-mix the channel at the receiver in order to perform symbol detection, the optimum detector is Maximum Likelihood (ML) where the receiver compares all possible combinations of symbols that could have been transmitted with the observed symbols. The complexity of this receiver is prohibitive if many antennas are involved and high order modulations are used. Receivers of practical interest for these techniques are linear receivers, either Zero-forcing (ZF) or Minimum Mean Square Error (MMSE) due to their lower complexity requirements with respect to a ML receiver. V-BLAST is another important receiver for SM techniques [12]. The performance is strongly dependent from the spatial correlation of the channel. Moreover, while SM techniques obtain the maximum multiplexing gains, the diversity performance is poor. With the advanced simulation chain 1, the performance of pure SM schemes with different receivers can be studied for an OFDM-based system complaint with the HIPERMAN standard. In particular, the performance sensitivity with respect to channel and system parameters, such as antennas spacing, number of scatterers' clusters, power delay profile, has been investigated. In Figure°1, the performance in terms of BER of MMSE and ZF receivers for a 3x3 QPSK configuration are shown and compared to a 64QAM Alamouti scheme (same bit rate for all schemes) in two different scenarios: 1) number of clusters is 1 (slightly correlated scenario); 2) number of clusters is 4 (more correlated scenario. It is evident the much higher sensitivity to the channel correlation of the SM schemes with respect to a diversity scheme such as Alamouti. Moreover, the MMSE receiver is less sensitive to the ill-conditioning of the channel matrix H with respect to a ZF. The improvement can be of about 3dB. In Section, the possibility to switch between a pure SM scheme and a pure diversity scheme is considered.



Figure°1 - Performance of Alamouti 16QAM, 3x3 QPSK with MMSE and ZF receivers in two scenario: 1) number of clusters = 1 (slightly correlated); 2) number of clusters = 4 (more correlated). Antenna spacing of 1 and 0.5 wavelengths at TX and Rx respectively.

3) Downlink beamforming

In the context of a fixed wireless downlink transmission, beamforming is a serious candidate to allow several users to communicate simultaneously. A novel algorithm was studied, which name is *Obele* algorithm. It was first presented in [18] and only requires that the base station knows the channel response of the downlink channel of each user. The implementation of this algorithm under the system C chain has lead to the advanced simulation chain 2. This chain implements a downlink transmission in which the BS communicates with two receivers. To generate independent data for these two receivers, all TX blocks –from `Source` to `CP append`– are duplicated into TX1 and TX2. The signals from TX1 and TX2 are multiplexed, weighted and added in a new block –`Antennas Multiplex`– to get the DL transmit signal. The block `Obele` computes the weights to be applied to the TX1 and TX2 signals. It was written in ANSI C and required algorithms to compute eigenvalues and generalized eigenvalues of complex general matrices. The block `Channel` has been modified in order to support a *N* (3, 4 or 5) transmit – 1 receive antenna system. Furthermore, the model of the channel is a 1 to 3 discrete paths with powers, delays and direction of departure (DoD) defined in the configuration file. There is no channel estimation implemented up to now; pilots are nevertheless inserted to obtain the correct number of carriers, a preamble is not inserted. Without loss of generality, we judge the performance by looking at only one receiver. Note that under non extreme conditions (extreme would be same DoD for both users), the convergence of the algorithm is really fast, about 3 iterations.

Another beamforming algorithm has been implemented to investigate the influence of intra-cell interference in section III. This optimal beamforming method not only steers nulls to interfering devices but also optimizes the signal-to-interference plus noise ratio (SINR) at the required station. For an unconstrained array, the weights that optimize the SINR are

$$\hat{\vec{w}} = \mu_0 R_N^{-1} \vec{s}_0$$

As the noise covariance matrix R_N does not contain any signal from the DoD. For an array constrained to have a unit response in the DoD, the constant μ_0 becomes

$$\mu_0 = \frac{1}{\vec{s}_0^{\,H} R_N^{-1} \vec{s}_0}$$

This is also known as the maximum likelihood (ML) filter, as it finds the ML estimate of the power of the signal source, assuming all sources as interferences. If the noise-alone matrix is not available, the total R (signal plus noise) can be used instead. In the absence of errors, the processor performs identically in both cases. The weights are then

$$\hat{\vec{w}} = \frac{R^{-1} \vec{s}_0}{\vec{s}_0^{\,H} R^{-1} \vec{s}_0}$$

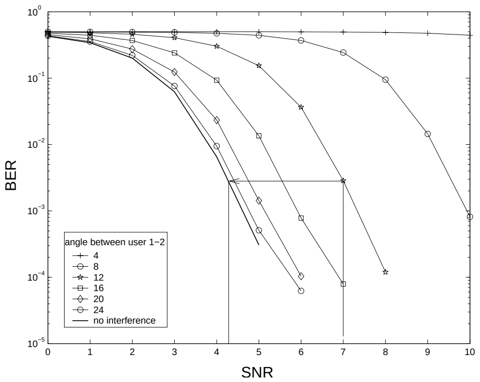
These weights solve the following optimization problem:

$$\begin{aligned} &\text{minimize} \quad \vec{w}^H R \vec{w} \\ &\text{subject to} \quad \vec{w}^H \vec{s}_0 = 1 \end{aligned}$$

Thus, the processor weights are selected by minimizing the mean output power of the processor while maintaining unity response in the DoD. The constraint ensures that the signal passes through the processor undistorted. The minimization process minimizes the total noise, including interferences and uncorrelated noise.

III. Evaluation of MTMR Multiple Access Interference

This chapter evaluates the impact of intra-cell interference on the bit-error-ratio (BER) and compares it with the impact of noise. During reception of data, an SS is experiencing certain signal strength (S) which is superposed by receiver noise (N) and interference (I). In the simulation chain, the received signal-to-noise ratio (SNR) during transmission is pre-defined by the initialization file and the block *Channel* is behaving accordingly. The interference caused by simultaneous transmissions to spatially separated subscriber stations is superposing the received signal depending on the optimized antenna pattern. In Figure°2 the BER of user 1 is plotted over a varying SNR in a two-user, QPSK ½ scenario. User 1 is fixed at zero degree while user 2 is moving from 2° to 30°. The curves have no significant difference for an angle greater than 30° because both users can be perfectly separated.

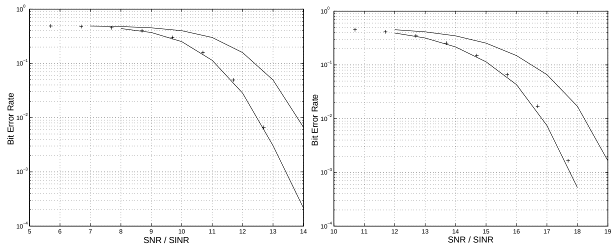


Figure°2 - BER over varying SNR and spatial separation

The signal and the level of interference depend on the antenna characteristics. It can be calculated with the amplitude factors of the antenna pattern. α_{nn} denotes the factor optimized for the direction of user n and received by user n, i.e. the signal. α_{kn} denotes the factor optimized for user k but received by user n, i.e. interference. The pattern is normalized that the maximum factor equals 1. Thus, SINR can be calculated:

$$SINR = \frac{S_{Rx}}{N + I_{Rx}} = \frac{S_n \cdot \alpha_{nn}^2}{N + \sum S_k \cdot \alpha_{kn}^2} = \frac{SNR \cdot \alpha_{nn}^2}{1 + \sum SNR \cdot \alpha_{kn}^2}$$

A separation of 12° in the two-user scenario leads to α_{11}=0.72767 and α_{21}=0.003133. Assuming a SNR of 7 dB an SINR of 4.239 dB can be calculated. This example is applied to Figure°2, where it can be seen that the original SNR in the two-user scenario leads to the same BER of $2.85*10^{-3}$ than the SINR without additional interference. Thus, the impact of interference caused by spatially separated SSs can be treated like noise. Simulations have been performed with other modulation and coding schemes and the result was confirmed. Results can be observed in Figure°3.



Figure°3 – 16QAM 3/4 and 64QAM 2/3 at 16° degree

The right curve gives the simulated BER for the SNR plus interferer at 16° degree. The left curve is the reference without any interferer. The crosses are marking the calculated values.

IV. Performance Evaluation of MTMR Techniques

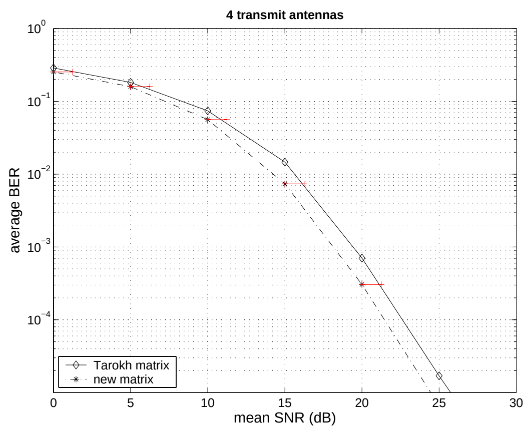
A. Enhanced space-time block codes

Within the framework of the STRIKE project new space-time coding matrices have been discovered. These new coding matrices possess the same properties in terms of the coding rate and the achievable spatial diversity gain as those presented in [16] but show the two following advantages:

a) Reduced digital signal processing requirements at both transmitter and receiver side, and
b) Improved bit error rate performance through exploitation of SNR gain.

The new matrices, which do no longer contain linear combinations of the constellation symbols, the associated addition and subtractions as well as the necessary scaling operations can be spared, which in turn leads to the reduction of the digital signal processing requirements The same applies for the receiver where the decision metrics for the new code matrices are simpler in terms of its complexity.

The improvement of the bit error rate performance is achieved through the power scaling that goes along with the new code matrices. The bit error rate performance of the new code matrix for 4 transmit antennas is compared to the state-of-the-art code matrices in the following figure, where the uncoded bit error rate is plotted versus the average symbol signal-to-noise ratio for the case of one single receive antenna.

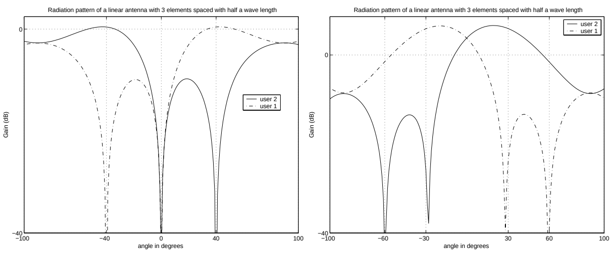


Figure°4 – SNR gain compared to conventional code matrices by Tarokh, example for 16QAM

The SNR gain for three transmit antennas amounts to approximately 1.1 dB whereas in case of four transmit antennas a gain of 1.25 dB can be observed. In the example illustrated in Figure°4, 16QAM symbol constellation was chosen to illustrate these gain. The SNR gain is, however, independent of the symbol constellation and therefore the same gains are achieved for other symbol constellations. For a more detailed description the interested reader is referred to [17], a paper that also appeared in the WPMC conference proceedings.

B. Enhanced beamforming techniques

Two sorts of simulations were run to validate the advanced simulation chain 2: the first to validate the algorithm and the second to compare the results obtained in this multi-user chain with those obtained with a single user one. Figure°5.a shows the transmit antenna pattern for receiver 1 and receiver 2, in a 2 paths channel, when the first path has a power of 0 dB, the second -10 dB, and the DoD are 40°/0° for receiver 1 and -40°/0° for receiver 2. We note that the second path, which is common to the two receivers, is cancelled and that all the interference is reduced to zero in the directions of interest. On Figure°5.b, the DoDs are -60°/-30° for receiver 1 and 60°/30° for receiver 2. All interference is cancelled. From this figure, we can conclude that the algorithm is very efficient in rejecting the interference. Furthermore, if α_{i1} and α_{i2} stand for the instantaneous attenuation of path 1 and 2 for receiver i, the algorithm ensures $E(|\alpha_{i1}|^2 + |\alpha_{i2}|^2) = 1$, if E() stands for the expectation. In such conditions, the Advanced Simulation Chain 2 ensures a perfect transmission of the data when no white noise is added, for one, two or three paths.

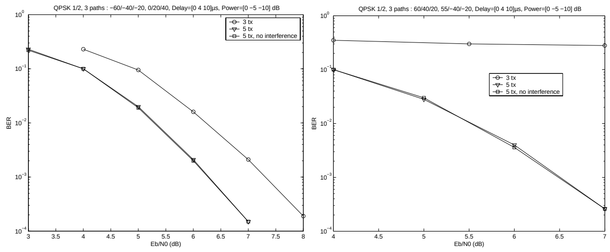


Figure°5 a, b – Antenna pattern in a 2 paths channel

The second set of simulations estimates the degradation of the Bit Error Ratio (BER). In a single path channel, 3 transmit antennas are enough to exactly reach the performance of a single user system. On Figure°6 is shown the BER in a three paths channel, for 3 and 5 transmit antennas at the BS. For comparison, the BER for a 5 TX antennas without interference is shown. The power of the paths is 0, -5 and -10 dB. In Figure°6.a, all the paths are well spatially separated. In Figure°6.b, the first paths are close to each other. We can note that 5 transmit antennas are enough to reach the no interference case in both cases, whereas a 3 transmit antennas system raises the BER.

C. Spatial multiplexing vs. diversity

Since the scenario under study is not characterized by high time variability, in order to get the best trade-off between multiplexing and diversity gain according to the instantaneous channel conditions, we have considered an adaptive scheme switching between an Alamouti scheme and a 2x2 SM scheme. Switching between some kind of transmit diversity/selection diversity and SM techniques according to some criteria has been proposed to provide a higher diversity order and make the system more robust to fading [19][20][21][22]. However, these schemes have been considered only for uncorrelated fading. In the wide range of correlated MIMO channels of a realistic BFWA system scenario, this solution is expected to give much higher benefits in terms of reliability.



Figure°6 a, b – BER performance comparison between 3 TX, 5 TX, and 5 TX without interference, 3 paths channel

In the considered scheme, the condition number of the current channel matrix is computed at the receiver and this information is sent back to the transmitter and used to select the transmission scheme according to the following criteria: if the condition number is higher than a given threshold, the Alamouti scheme is used; SM is used otherwise. Modulation scheme is the same. When a QPSK modulation is assumed, with an Alamouti scheme a rate R=2 is achieved. In a pure SM scheme 2x2, R equals 4. In the switching scheme R is less than 4. Therefore, the multiplexing gain is reduced in order to get a higher diversity order. In Figure 7 the performance of the switching scheme is compared to the ones of a pure Alamouti scheme and a pure 2x2 SM scheme with a QPSK modulation. The threshold on the condition number has been chosen with the aim to get a diversity order close to the one of an Alamouti scheme. It can be observed that a good robustness to fading can be achieved at the price of a slight reduction of the multiplexing gain (reduced average data rate with respect to the SM scheme). Other results, which are shown in [23], highlight the higher price in terms of multiplexing gain that must be paid in the strongly correlated case. However, it still worth using the switching scheme with respect to a pure Alamouti. Other simulations in a highly time variant channel (Doppler frequency of around 150 Hz) have shown the efficiency of the switching scheme is very much reduced. However, we are proposing to use this scheme in a BFWA scenario where high time variability is not expected (Doppler frequency of 50 Hz).

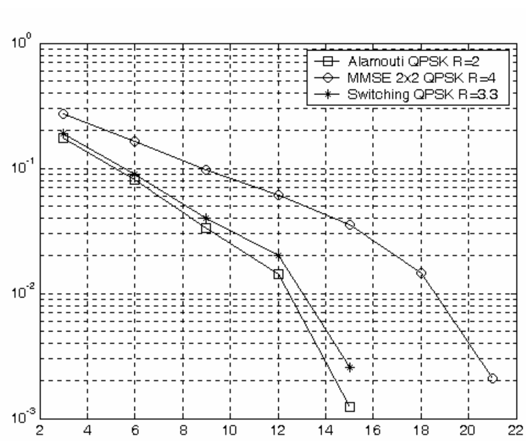


Figure 7 - Performance of pure Alamouti 2x2 with MMSE and the switching scheme for a channel modelled by a number of clusters = 1 (slightly correlated).

V. CONCLUSION

In this paper we presented the enhanced link level simulation platforms developed within the STRIKE project. The simulation platform includes a HIPERMAN and HIPERLAN/2 compatible reference chain as well as advanced simulation chains for the space-time coding, Spatial multiplexing and beamforming algorithms as well as a dynamically reconfigurable simulation chain with MAC layer signal generation for the evaluation of the impact of the MTMR techniques on the MAC layer level.

In advanced future system level simulations the PHY layer behaviour is modelled by means of BER(SNR) curves. It turned out that for such simulations the impact of inter-cell interference caused by spatially separated SSs can be treated like noise.

The beamforming algorithm implemented in the Advanced Simulation Chain 2 allows a perfect interference cancellation in a DL transmission between a BS and 2 receivers, even in a multipath channel. The computing cost is not too high thanks to the fast convergence of the algorithm.

Moreover, in the slowly time varying and highly correlated channel, which is typical for a HIPERMAN scenario, adaptive schemes that switches between a pure SM scheme and a Alamouti scheme, which is already included in the standard, can help in getting higher data rates while keeping a good robustness of the system to fading.

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