PERFORMANCE VERIFICATION OF MIMO CONCEPTS USING MULTI-DIMENSIONAL CHANNEL SOUNDING

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ABSTRACT

The advances in multi-dimensional channel-sounding techniques make it possible to evaluate performances of radio multiple access and signal processing schemes under realistic propagation conditions. This paper focuses on the methodology how recorded impulse response data gathered through multidimensional channel sounding field measurements can be used to evaluate link- and system-level performances of the multiple-input multiple-output (MIMO) radio access schemes. The method relies on offline simulations. It can be classified in between the performance evaluation using some predefined channel models and the evaluation in field experiments using a set of prototype hardware. New aspects for the simulation setup are discussed, which are frequently ignored when using simpler model-based evaluations. Example simulations are provided for an iterative (”turbo”) MIMO equalizer concept.

1. INTRODUCTION

The increase in spectrum efficiency by using simultaneous transmission of multiple data streams from different antenna elements [1] is known as a key technology for new air interfaces oy wireless networks beyond 3G. The transmitted signals are intentionally not orthogonal in any of the conventional communication signal dimensions, i. e., by time, frequency, or code. Conceptually, the multipath propagation of the radio channel gives rise to different spatio-temporal signatures for the different transmit data streams, which permits a receiver equipped with multiple antennas to separate those data streams from the received signal mixture. Keeping this in mind, it is not really surprising that the performance of a MIMO system will strongly depend on the radio channel conditions. A key question for a system implementation is therefore, do we find practically feasible schemes that are sufficiently robust for this task? Or somewhat related, what specific features are required for a practical MIMO system to work reliably under a wealth of various propagation conditions?

This paper approaches those questions by describing a realistic simulation methodology which is focused to gain insights into propagation related effects of a specific MIMO transceiver design example. The idea is to use the results of double-directional real-time channel sounding experiments [2] for MIMO link-level simulations.

Wideband MIMO receivers depend on the joint spatial *and* temporal multipath structure at the transmitter (Tx) side as well as the receiver (Rx) side of the radio link. Hence, evaluating the performance of a wideband MIMO detection scheme by means of simulations requires much more detailed knowledge and exactness of the channel than conventional single antenna systems or systems with multiple antennas only at one side of the link. This makes high demands on an appropriate MIMO channel model, which is currently a hot topic in the research. However, the validation of the different proposals frequently relies on for the system design rather abstract benchmark criteria, like the channel capacity [3, 4]. The corresponding outcome of a channel model, which is parameterized to a measured scenario, is thereto compared with the results from real measured data. Although the channel capacity seems to be the performance criterion *par excellence* when considering MIMO systems, this does not necessarily imply, that a good match in modeling the capacity guarantees a sufficient match to model the spatio-temporal channel structure for a particular transceiver signal processing scheme. For this reason, a good practice is the validation of new models in terms of the performance results of system simulations. This is possible by comparing the model based results with the results obtained when directly using the data of representative example environments, which requires that the model has been parameterized to the measured data.

The paper is organized as follows: Section 2 describes important issues for the MIMO measurement procedure and the concepts for measurement based link-level simulations. Example simulation results for a wideband MIMO system and a brief summary of the Turbo MIMO Equalizer based transceiver concept are shown in section 3. Some conclusions are given in section 4.

2. CONCEPTS FOR SYSTEM EVALUATION BASED ON MEASUREMENT DATA

2.1 Realistic MIMO channel modeling

Propagation modeling relies on a system-theoretic view on the wave propagation from the transmit antenna to the receive antenna. The wave propagation effects like scattering, reflection, and diffraction can be described by the complex channel impulse response. A statistical characterization of the impulse responses preserves the space-continuous nature of the electromagnetic wave propagation effects, but does not lead to an intuitive interpretation. A more descriptive representation is possible by approximating the wave propagation as a superposition of discrete partial waves [7, 8, 9]. Since the formation of the partial waves is related to an instantaneous physical constellation of the antennas and all other objects in the radio scenario, any change in the distance to be travelled by a partial wave leads to a Doppler shift in their complex amplitude. In a MIMO system, multiple antennas are placed in the wave field, which effectively carry out a spatial sampling of all the individual partial waves. Hence, an exhaustive description requires for each partial wave p the specification of the direction of arrival (DOA) at the receive antenna in azimuth and elevation (ψ_{R_p} and ϑ_{R_p}) and equivalently the direction of departure (DOD) at the transmit antenna (ψ_{T_p} and ϑ_{T_p}), the propagation delay time τ_p, the Doppler shift α_p and the complex amplitude matrix γ_p, whose 2x2 entries quantify the co- and cross-polarization components. This yields the following signal model for the double-directional radio channel:

$$\begin{aligned}\mathbf{h}\left(\alpha,\tau,\psi_R,\vartheta_R,\psi_T,\vartheta_T\right) = \\ \sum_{p=1}^{P}\gamma_p\,\delta\left(\alpha-\alpha_p\right)\delta\left(\tau-\tau_p\right)\delta\left(\psi_R-\psi_{R_p}\right) \\ \delta\left(\vartheta_R-\vartheta_{R_p}\right)\delta\left(\psi_T-\psi_{T_p}\right)\delta\left(\vartheta_T-\vartheta_{T_p}\right)\end{aligned} \quad (1)$$

The identification of this model from measurements could be seen as the ultimate goal in propagation modeling, because it abstracts from a particular antenna and allows to derive all other types of channel models. The required procedures are very challenging. Thus, simpler approaches are frequently adopted.

Both deterministic and stochastic MIMO channel models have been proposed in the literature (see [10] for an overview), each with specific focus aspects and limitations. Their validation and, as the consequence thereof, modification is still a subject of intensive research.

2.2 MIMO channel measurement

A modern multidimensional channel sounder device like the RUSK MIMO [11] from MEDAV is capable to capture the channel characteristics for all dimensions involved in Equation (1) completely in a Nyquist sense. The measurement principle is described in [2]. Multiple antennas at the transmitter as well as the receiver side are managed by fast antenna multiplexing which is synchronized to the test signal period. For the extraction of the multi-dimensional path parameters in Equation 1 from the measured frequency responses, high resolution parameter estimation algorithms have been developed and successfully applied [12]. A mandatory prerequisite is the use of carefully designed measurement antennas.

The selection of suitable antennas is of specific importance, because it depends on the objectives of the measurement and the intended usage of the data. It should be emphasized that certain use cases can be mutually contradictory. E.g., for investigations of space diversity processing, an antenna element spacing of multiples of the wavelength λ is usually desired. On the other hand, space coherent processing and high resolution parameter estimation of the data is only possible if the element spacing is smaller than $\lambda/2$. The ability for a 3-dimensional resolution of the DOD's and DOA's is only possible if the array has an aperture in the horizontal as well as the vertical space dimension.

Another antenna related issue is the field of view both for the individual elements and the antenna array as a whole. Three possible combinations are relevant: In planar array structures (linear and rectangular arrays) the elements and the array cover only a sector. Circular arrays are constructed to have a 360° field of view with either directional elements (patch arrays, multibeam antennas) or omnidirectional elements (dipole arrays) [2].

In the sequel, two different approaches are described in order to derive the channel coefficients on the basis of measurements in a real-field scenario.

2.3 Data based channel modeling (DBCM)

The DBCM method derives the channel coefficients directly from the measurement data array D [1]. The following discussion describes a few aspects to be considered for this method. The minimum analysis requirement is to verify the data for a sufficient signal-to-noise ratio (SNR). In a low SNR constellation, the measurement noise peaks act like multipath components in the simulation. Hence, those data have to be sort out. Important as well is the limitation of the delay range of the impulse responses to the effective delay window. This denotes the delay span containing significant multipath energy. The measurement noise outside the delay window virtually introduces additional noise in the simulation. Thus, it is important to ensure a reasonable ratio of the measurement SNR and the maximum target SNR in the simulation. The delay window selection serves the additional purpose to compensate the base propagation delay. In a transmission system, this is the task of a rough delay control. Since a frequency domain measurement method is applied, basic Fourier transform properties are to be considered during the measurement and the data processing. Therefore, changes of the base propagation delay during the observation time can also lead to a cyclic shift of multipath components w.r.t. the measured delay interval. Another Fourier related processing requirement is to use window functions with a smooth tapering for selection operations in the delay as well as the frequency domain. This is most easily accomplished by integrating the pulse shaping filter at the Tx and the receive filter of the system to be simulated into the preprocessing. Absorbing Tx and Rx filters into the channel impulse response is also required to derive the channel coefficients with symbol rate tap spacing. This simplifies the simulation, because the subtleties of symbol timing recovery can be excluded when the respective implementation issues are beyond the scope of investigation.

It has already been stressed, that the antenna configuration is of exceptional relevance for MIMO systems. Although DBCM lacks the flexibility to incorporate arbitrary antenna properties after the measurements have been completed.

2.4 Measurement based parametric channel modeling (MBPCM)

This method belongs like DBCM to the category of deterministic channel models. It is based on characterizing the wave propagation in a particular measurement environment by a finite number of discrete partial waves as in Equation 1. Thus it is a two step procedure with a parameter estimation step and a synthesis step [8]. Since the underlying model does not depend on specific antennas, this model allows to consider the antenna related effects in the synthesis step[2]. This increases the flexibility for system design oriented simulations significantly, because the antenna setup can be easily varied.

Since the path parameters together with the complex amplitude of each path describe the wave field around the Tx as well as the Rx antenna arrays, they can be used to make a synthesis of MIMO impulse responses for different antenna array shapes than that of the measurement arrays. Even a variation of the array position in a small surrounding of a few λ or a change of the orientation is possible. Assuming plane wave fronts and only one polarization component, the synthesis can be performed by using

$$h_{mn}(l) = \sum_{p=1}^{P}\gamma_p\,g(lT-\tau_p)\,a_{T_n}(\psi_{T_p},\vartheta_{T_p})\,a_{R_m}(\psi_{R_p},\vartheta_{R_p}), \quad (2)$$

where γ_p is the complex path weight of path p with delay τ_p, and a_{T_n} is the nth element of the Tx array re-

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[1] Appropriate sample data can be downloaded free of charge from [11].

[2] An obvious limitation is that the field of view of the measurement antennas is larger or equal to the field of view of the antennas in the synthesis step and the required aperture dimensions are covered.

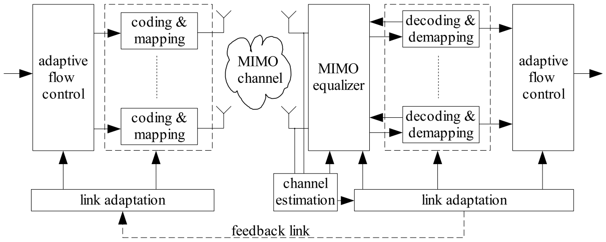

Figure 1: Broadband MIMO system based on Turbo MIMO Equalization (TME)

sponse vector in azimuth and elevation of the system antenna to be simulated. Likewise the Rx array response is contained in a_{R_m}. The array response may also contain a non-homogenous directional element characteristics. $g(t)$ is the continuous time impulse response of the combined transmit and receive filters, which is sampled in multiples of the symbol period $T = 1/f_S$. It has the same function like in the DBCM method and a raised cosine filter is usually applied.

Novel results extend the MBPCM method to include diffuse scattering components by superimposing a stochastic part whose characteristic parameters are estimated from the measured data as well [13].

2.5 System specific aspects of link-level simulations

The use of measured channel data in the simulation requires the consideration of some basic real-world transceiver functions. A simplified implementation, based on *a priori* knowledge is desirable and legitimate, as long as the corresponding transceiver function itself is not to be examined. In model based simulations most of this functionality is not required, because the channel models are usually adapted to the transmission system and abstract the physical propagation background. Three aspects are discussed below, that have to be considered in the context of a specific system design.

The system model introduced so far always assumed a time-invariant channel. This is a reasonable standard assumption for a wideband system with burst-oriented transmission. The following simple calculations motivate this: The channel can be approximated time-invariant over one burst, if the carrier phase uncertainty $\Delta\phi_c$ due to the Doppler effect is negligible over the burst duration. This can be expressed by the product of the Doppler bandwidth B_D and the burst duration T_B, $\Delta\phi_c = 360^\circ \cdot B_D \cdot T_B$. On the one hand, expected Doppler bandwidth is larger the higher the system's carrier frequency and higher the supported maximum speed of the terminals. On the other hand, the higher the data rates the shorter is the burst duration for a typical amount of data symbols. For the example simulations in section 3, the following numbers give an illustration: The maximum supported terminal speed should be 10 km/h, yielding a Doppler bandwidth of ±48 Hz at 5.2 GHz carrier frequency. The assumed maximum number of data symbols per burst and antenna (including coding) is 2048 symbols, hence the burst duration at 20 Msymbols/s is 102.4 μs. Consequently, $\Delta\phi_c = \pm 1.8^\circ$, which is small compared to the data symbol's phase separation in all considered symbol alphabets.

The measured impulse responses have usually a significantly longer delay window than the temporal memory length of the receivers $T_R = LT$. Hence, a delay control must ensure, that the receiver processing is temporally synchronized to that portion of the delay profiles offering the optimum performance. This task is similar but not identical to the problem of the delay window selection during the data preprocessing described in section 2.3. Given the channel coefficients $h_{mn}(l)$, the delay control determines the start of the delay span of length T_R containing the maximum energy. For the P2P setup, all coefficients are spatially averaged to obtain one single delay control value. For the MU setup, each users coefficients are averaged to obtain one delay control value per user.

The power control is responsible for adjusting the desired receiver signal to noise ratio (SNR). For the MU setup, an ideal power control adjusts the transmit power at each transmit antenna such that the mean received power over all elements is identical for all users, $\sum_{m=1}^{M} P_{mn} = M/N$. While this holds constant the total transmit power independently of the number of users, the total received power increases with the number of receive antennas. This is a pragmatic rule, which keeps the spirit behind the MIMO theory to increase the channel capacity by adding parallel channels at constant transmit power, while retaining the physical fact, that the total received power increases with the number of antennas located in an electromagnetic field of a given strength. For the P2P setup a modified power control scheme with lower complexity seems attractive, which adjusts the total received mean power while transmitting identical powers by each antenna, $\sum_{m=1}^{M} \sum_{n=1}^{N} P_{mn} = M$.

3. EXAMPLE ON LINK LEVEL SYSTEM EVALUATION

This section covers by means of examples the strategies to evaluate the bit error rate (BER) performance of systems based on the Turbo MIMO Equalizer (TME) concept as introduced in the next section. The focus lies on characterizing the robustness w.r.t. varying propagation conditions and the influence of several design options. All simulations are based on measured channel data at 5.2 GHz carrier frequency. The assumed symbol rate is 20 Msym/s (β=0.25).

3.1 Turbo MIMO Detection

The considered MIMO transmission system based on an iterative receiver concept was inspired through [14], based on a proposal of an iterative CDMA receiver [15]. The proposed MIMO system can be applied to multiuser (MU) or point-to-point (P2P) MIMO as well as a multiuser MIMO setups. In order to simplify the description, the TME based receiver is assumed at the base station (BS) of a cellular system or at the access point of a wireless local area network (WLAN) system. In the MU setup the multiple transmit data streams originate from several single antenna user terminals. The goal of adopting the MIMO approach in this setup is to maximize the system capacity in bits/s/Hz per radio cell. The P2P setup allows to maximize the link capacity in bits/s/Hz for a single link between a user terminal equipped with multiple antennas and the BS. The multiuser MIMO setup combines both features by allowing several user terminals with multiple antennas. In the sequel the P2P MIMO configuration is considered and is shown in Figure 1.

The receiver consists of two main parts: the MIMO SC/MMSE equalizer producing soft outputs and the soft input soft output channel decoder. Both are linked in order to exchange reliability information for the coded bits and together they perform the turbo MIMO detection. The reliability information is used within the MIMO equalizer block in order to perform a soft interference cancellation (SC) step of the interference components, which arise from inter-symbol interference (ISI) and multiple access interference (MAI). In the high data rate point-to-point (P2P) MIMO case the MAI are caused by the multiple antennas of one user transmitting signals at the same time and frequency slot. A spatial-temporal minimum mean square error (MMSE) equalizer subsequently follows the SC step to minimize remaining ISI and MAI components at the filter output. For each trans-

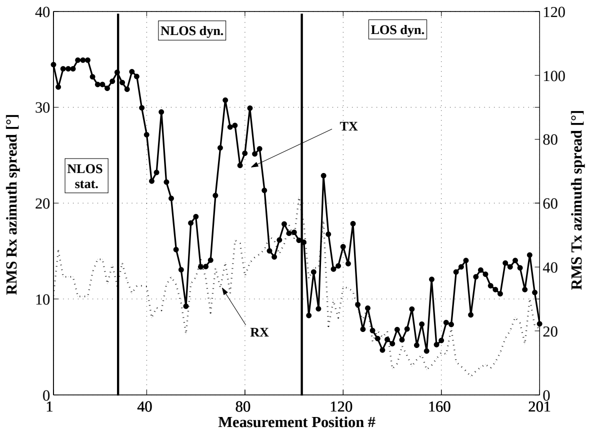

Figure 2: RMS Tx and Rx azimuth spread along the entire measurement track

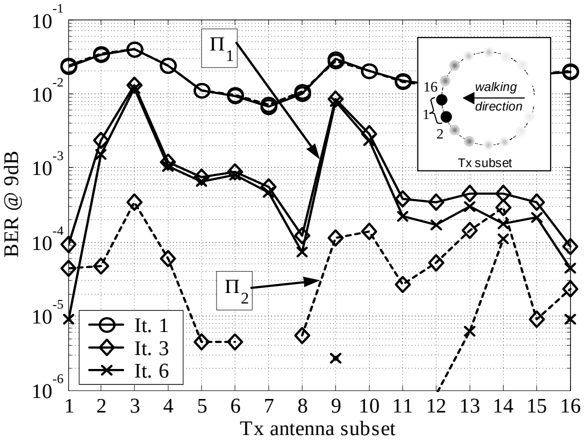

Figure 3: Effects of small antenna displacements on the performance of a 2/2 TME

mitted data stream one filter output exists and consequently one decoder embedded together with de-interleaver and interleaver in an iterative feedback loop. In the first iteration no SC step can be applied due to the fact that no reliability information of the coded bits is available at this point. Therefore, the MMSE filter alone plays the role to suppress all interferences.

For the link-level simulations following assumptions have been made: each data stream of the TME system is convolutionally encoded (code rate 1/2, constraint length 3, $G=[7,5]$) and random interleaved. Gray mapping is used to derive the symbol constellations of the higher modulation schemes. On the receiver side the channel decoding part was performed by the max-log-map algorithm and perfect channel knowledge is considered.

3.2 Small-scale antenna displacement

The results in this section highlight the performance sensitivity of a 2/2 TME system regarding small antenna displacements. Furthermore, the influence of employing identical (Π_1) or different (Π_2) interleavers for the detection of two QPSK modulated transmit signals is depicted. The selected P2P MIMO measurement can be classified as a micro cell outdoor scenario for a WLAN application with low mobility. A detailed description can be found in [11] and [16]. The measurements were performed utilizing an UCA consisting of 16 omnidirectional elements as the Tx antenna. According to the small sketch illustrated in Figure 3, 16 different subsets are available consisting of two closely spaced elements (distance of 0.38λ). From subset to subset the two elements are changed only by one antenna position. On the receive side the two outer elements (distance of 3.46λ) of an 8 element ULA were selected for the simulations. The position of this antenna was fixed, whereas the transmitter was passing at a distance of 10 meters under a transition from NLOS to LOS propagation conditions. The multipath propagation can be characterised by the RMS Rx and Tx azimuth spreads in Figure 2. For the simulations 201 snapshots along the measurement track were selected and the SC/MMSE equalizer was equipped with $L = 5$ delay taps.

The continuous small antenna displacements over the entire UCA show considerable performance differences for the TME with identical interleavers. In Figure 3 the BERs are shown for each subset at 9 dB SNR. For the Tx subsets no. 3 and 9 the transmission completely failed, but subsets 8, 16 and 1 showed reasonable BER's. In general, for all Tx subsets the final detection results are reached after three iterations and additional iterative processing shows no further improvements. Considering that the antenna displacements follow a circular shape and observing the course of subsets with low and high BER's, it seems that the same distinct directional propagation effects cause the similar results for equally oriented Tx subsets. The TME utilizing different interleavers shows significantly better performance with an increasing number of iterations. This can be explained as follows: The similarity of the power delay profiles for each transmit antenna tends to produce erroneous received symbols at the same positions within the two transmit streams to be detected. In a TME with different interleavers the resulting error sequences at the input of the channel decoders are differently permuted within the two streams (see Figure 1). Hence, the computation of the *extrinsic* soft information by the channel decoders is based on different temporal *a priori* reliablity patterns in the two streams to be decoded. According to the information-theoretic comprehension of turbo equalization/decoding, the iterative processing gain strongly depends on the exchange of *extrinsic* information between the SC/MMSE equalizer and the SISO decoders. For the MIMO case, this comprises always the additional *extrinsic* information of the respective other streams. The computation of this *extrinsic* information is more effective if the independence between the streams is increased by using different interleavers.

3.3 Modulation schemes

Based on the NLOS part (60 snapshots) of the MIMO channel considered in section 3.2 the performance of a 3/3 TME with the different modulation schemes BPSK, QPSK, 8-PSK and 16-QAM is evaluated. Additionally, an investigation of the impact of using different numbers of delay taps ($L = 5$ and $L = 9$) for the receiver's equalizer is carried out. All simulations utilize different interleavers for the transmit signals and the amount of symbols per transmit stream (512) is held constant. Hence, the effective number of information bits depends on the considered modulation. After 6 iterations the results in Figure 4 show clearly that a parallel transmission of three independent 16-QAM modulated signals in the considered MIMO channel can be successfully performed with the TME concept using 9 delay taps for equalization. Furthermore it is discovered that the same BER results can be gained for the BPSK and QPSK cases, regardless of using an equalizer with 9 or only 5 delay taps. But for the 8-PSK and 16-QAM modulation a remarkable gap between the curves for the different equalizer lengths is observed.

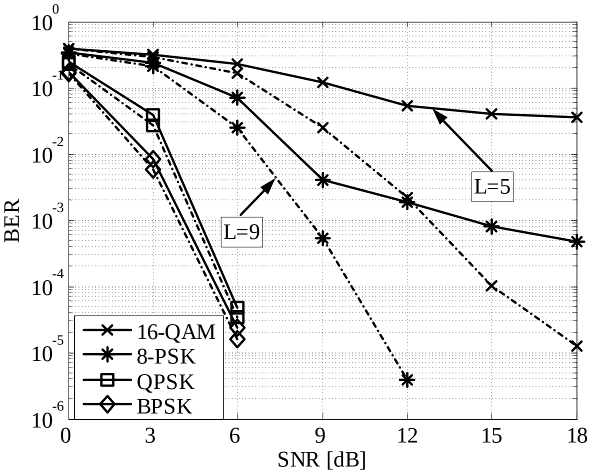

Figure 4: Performance of a 3/3 TME for various modulation schemes and different numbers of delay taps

4. CONCLUSION

For a successful MIMO system development more efforts than ever before have to be spent on the channel modeling side, because the multipath propagation itself turns into a key component of the transmission system. Realistic models are extremely complex and still under investigation. More open issues exist for the modeling of transitions from one propagation situation to another, e.g., from a NLOS to a LOS situation, or from an open place in a city into a narrow street. Consequently, new transceiver concepts should always also be verified by using channel measurements in the appropriate system deployment scenarios such as high-speed public access scenarios (e.g., access point to car), public open indoor areas (e.g., airport), or factory halls.

Two different methods for measurement based MIMO channel modeling have been presented and compared. Their application to the performance evaluation of the turbo MIMO equalizer concept revealed a reasonable performance, but also a sensitivity to the propagation conditions. The observed results suggest that advanced link adaptation algorithms are required to prevent excessive BER's. The causality of certain performance effects can be traced back to the instantaneous channel conditions by referring to the results of a propagation analysis, either by high resolution estimation of multipath parameters or by non-parametric statistical investigations. This provides significant insights both for the verification and enhancement of channel models and for the optimization of particular Tx and Rx signal processing schemes.

According to the opinion of the authors, realistic channel modeling in MIMO systems is presently only possible with a balanced mix of a deterministic modeling approach for representative scenarios and the frequently favored stochastic modeling approaches. The huge potential of measurement based methods for fast and reliable performance evaluation has been not yet fully recognized in industry but the acceptance is growing.

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