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Uwe Trautwein¹
Christian Schneider²
Gerd Sommerkorn²
Dirk Hampicke²
Reiner Thomä²
Walter Wirnitzer¹

¹ MEDAV - TeWiSoft
Ehrenbergstr. 11, D-98693 Ilmenau, GERMANY
Phone: + 49-3677 668 433
Fax: + 49-3677 668 676
Email: uwe.trautwein@tewisoft.de

² Ilmenau Technical University
FG EMT, POB 100565, 98684 Ilmenau, GERMANY
Phone: + 49-3677 69 1157
Fax: + 49-3677 69 1113
Email: christian.schneider@tu-ilmenau.de

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¹ MEDAV – TeWiSoft, Ilmenau, GERMANY, Email: uwe.trautwein@tewisoft.de

² Ilmenau Technical University, GERMANY, Email: christian.schneider@tu-ilmenau.de

Abstract: Realistic modeling of the radio wave propagation is an essential prerequisite for the evaluation of different concepts for future wireless communication systems. Thus, the modeling approaches should be based on channel sounder measurements. Depending on the specific aspects of a system to be investigated, there exist individual requirements for setting up the measurement procedure and the measurement equipment. In a first part, the paper gives an overview on the various applications of channel sounder measurements and the corresponding considerations for the measurement setup. Those applications are high resolution parameter estimation of multipath propagation, MIMO channel capacity estimation and channel modeling for link- as well as for system-level simulations. In a second part, the paper presents examples of different measurements carried out at 5.2 GHz using the MEDAV RUSK-ATM channel sounder. Real-time SIMO as well as MIMO measurements are described using a large variety of antenna array constellations. Corresponding sample data files including a documentation can be downloaded free of charge for scientific purposes at <http://www.channelsounder.de>.

1 Introduction

Wireless communication systems employing multiple antennas at either one end (single-input multiple-output, SIMO) or both ends (multiple-input multiple-output, MIMO) of a link, are expected to meet many of the requirements for future applications, such as providing high data rates, a reasonable spectral efficiency, robustness with respect to different propagation conditions and interference as well as moderate power emission. The theory and the technological advances are being developed for new processing concepts that go far beyond traditional simple diversity schemes. The evaluation of different concepts in early stages can be made realistically by using appropriate measurements of the radio wave propagation. The availability of broadband, real-time MIMO channel sounders such as the MEDAV RUSK-ATM opens up the multiple dimensions of the mobile radio channel that can be exploited using space-time signal processing. The evaluation of a new system proposal has always to consider multiple levels. The investigation of competing signal transmission schemes such as single carrier, multicarrier or CDMA is required not only on the link-level but also on the system-level. This has consequences for the measurement setup as well as for the propagation modeling methods.

The identification of a parametric model of the double-directional wave propagation could be seen as the ultimate goal in channel measurement. Usually, this means the wave propagation is completely modeled on the "ray-level" by individual propagation paths. Each path component is characterized by the 3D spatial directions of departure at the transmitter (Tx) and the directions of arrival at the receiver (Rx), the path delay, the complex transmission weight factor, ideally including the four polarization components, plus the instantaneous Doppler shift in case of a time-variant scenario. The reason for denot-

ing this kind of model as ultimate is, that it offers the flexibility to derive all other categories of modeling approaches for more specific considerations. Furthermore it is independent of the measurement antenna characteristics [11] which provides the possibility of a free choice of the antenna constellation in later evaluations by embracing arbitrary antenna characteristics. But there are reasons why this complete parametric model is hard to obtain for real-world situations. On the one hand, they are related to the difficulties in measuring all the dimensions involved. On the other hand, a discrete multipath model is always an approximation of the real-world propagation phenomena. Environments with a lot of diffuse scattering or an overwhelming number of paths can only be poorly fitted to this kind of model.

As a consequence, alternative realistic propagation modeling methods are desired. This includes reduced parametric models with limited dimensions, parametric statistical models without concrete physical propagation background, as well as the direct use of measured impulse response data. It should be noted that the validity of one of the reduced parametric models has always to be related to a particular application. This is an issue for further research. For setting up a channel sounder measurement, the selection of the antennas is especially important. The parametric estimation of ray-level models requires the use of specifically designed high-resolution measurement antennas. In contrast, application specific antennas are needed if the sounding data should be used directly.

2 Channel Sounder Data Applications

2.1 Multidimensional Parameter Estimation of Multipath Propagation

The multidimensional data model of mobile radio channels is given by a number of propagation paths which are described by the parameters DOD (direction of departure at Tx), DOA (direction of arrival at Rx), TDOA (time delay of arrival), and Doppler. Both, DOD and DOA, are given by azimuth and elevation. The resulting 6-dimensional parameter estimation problem is typically solved by multidimensional ESPRIT, SAGE or iterative ML procedures [3], [9]. Subsequently, the 2×2 polarimetric path weight matrix is estimated [5]. High DOD/DOA resolution requires sophisticated antenna architecture design, mechanically and electrically stable construction and precise calibration. Since there is always a tradeoff between various specifications including resolution, measurement time, availability and costs, there is a wide variety of useful antenna array architectures. Let's discuss some exemplary design considerations:

- Uniform linear arrays (ULA) and uniform rectangular arrays (URA) always have limited viewing angles. Therefore these arrays are well suited to represent a base station's (BS) view to the channel. Contrary to that, circular arrays have a full field of view. They can be used to represent the mobile station's (MS) view.
- Double directional modeling requires arrays at both sides of the link and MIMO operation of the sounder. For cellular system consideration, a combination of planar and circular arrays is adequate, whereas for ad-hoc peer-to-peer networks identical circular arrays are most preferable.
- Mainly for micro- and pico-cell scenarios, estimation of the elevation is involved in addition to the azimuth. This requires URA, cylindrical or spherical arrays.
- Full polarimetric analysis of the propagation requires not only polarimetric reception but also polarimetric excitation of the channel. This is especially true for omnidirectional excitation where we need a two port antenna which launches both orthogonal

polarized waves with omnidirectional characteristics and, thus, requires a 2xM MIMO sounder.

- High and reliable resolution in terms of separation capability of closely spaced paths and low probability of outliers, requires a minimum of antenna element aperture size, a maximum of antenna element separation, low antenna element coupling, and precise calibration.
- The characteristics of the antenna elements depends on the basic element design (dipoles, patches, slots, etc.) It has a strong influence to estimation ambiguities, probability of outliers and polarization resolution capability.
- ESPRIT requires shift invariant array architectures. Therefore, its application is restricted to uniform linear or planar arrays (ULA / URA) or to circular uniform beam arrays (CUBA) [3]. CUBA are circular arrays with a common phase center of all elements and some directivity of the elements. ESPRIT relies on identical beam patterns of all elements in the aperture domain. Therefore, a parametric calibration procedure is required which equalizes the beam patterns and essentially removes the mutual coupling.
- SAGE and other iterative ML procedures are more flexible in terms of applicable array architectures (e.g., circular structures of patches can be used). In this case, calibration means that the array manifold must be known (including amplitude and phase), measured in a well defined anechoic environment. However, the basic influence of the array architecture to resolution and reliability still holds as discussed above.

2.2 MIMO Channel Capacity Estimation

It is commonly anticipated that MIMO transmission using multiple antennas at both the transmitter and the receiver considerably enhances the link performance in terms of achievable data rates and spectral efficiency. This results not only from an increased SNR and SINR (signal-to-interference plus noise power ratio) because of beamforming and interference reduction, but also from a potential MIMO capacity gain by multiplexing of the transmitted data over spatial sub-channels. The achievable MIMO capacity gain depends on the multipath characteristics of the propagation channel (the number of the useful propagation paths) and on the properties of the antenna setup (e.g. on the architecture of the antenna arrays which includes the number and the arrangement of the antennas and their radiation characteristics). For a certain antenna architecture the channel matrix can be recorded from MIMO sounder trials and the resulting capacity can be estimated from its Eigenvalue statistics [12]. For system optimization it makes sense to distinguish between the MIMO capacity resulting from beamforming only and the capacity which results from data multiplexing. Also full, incomplete or missing knowledge of the channel matrix at the transmitter has to be considered.

As mentioned in the introduction, different antenna setups should be considered for measurements with the objective of MIMO capacity investigations: high resolution antennas and antennas for system applications.

Channel capacity estimations based on measurement trials using application specific antennas represent the capacity, which can be reached for this particular system constellation. For example, a conceivable setup consists of a large regular structured antenna (such as ULA or URA) playing the role of a base station or access point, and small arrays at the mobile terminals. Normally, these antennas offer a limited viewing angle to the channel and do not capture the complete spatial and temporal multipath diversity of the given propagation environment. Furthermore, they can be optimized based on system design

objectives, in order to maximize the capacity (e.g. by maximizing the spacing between elements and by exploiting beam- and polarization diversity), to reduce system cost (by minimizing the number of the channels), and to cope with the physical size and shape of the respective devices.

Another option is to use high resolution antennas that are optimized for maximum resolution of the propagating waves which are passing some well defined measurement volume. In this case the goal is to reach measurement results, which are independent of any antenna structure or system application, and hence, can be interpreted as the intrinsic capacity of the channel [13]. The estimated intrinsic capacity can be considered as an upper bound on the available performance which depends only on the propagation environment. In addition, multidimensional channel parameters are explicitly available only if high resolution antennas are applied. This advantage allows, e.g., the interpretation of the estimated channel capacity results in terms of angular, delay, and Doppler statistics, such as spreads and correlations.

2.3 Link-Level Simulations

Link-level simulations evaluate the performance of different candidate signal transmission and detection schemes in various propagation environments with a range of parameter settings. The most important performance figure is the bit error rate (BER). The reliability of the results of link-level simulations strongly depends on a proper modeling of the radio wave propagation. The required level of detail and the necessary classification of propagation environments for defining accurate statistical channel models increases significantly if systems with a single antenna at both ends of a link are extended to systems with multiple antennas at one end of the link, and moreover extended to MIMO systems. The reason is that the latter systems rely more and more on the spatial characteristics of the wave propagation. By means of multidimensional channel sounding measurements, the impulse responses from each transmit antenna element to each receive antenna element can be detected. With that, real field performance of the detection algorithms can be obtained through off-line simulation. This is much more cost effective and flexible than field trials with hardware demonstrator systems.

The following items summarize some important aspects for performing measurements for link-level simulations [7], [8].

- The measurement setup should resemble a potential system application setup. Issues to be considered are among the following: What is the characteristic deployment of the system (cellular or ad-hoc network, cell size and potential BS sites, indoor or outdoor)? Is the system operated with or without co-channel user signals? What is the spatial separation of the co-channel signals (a MIMO transmitter uses closely spaced antennas, for space division multiple access systems the users are distributed within a hypothetical radio cell)? What degree of user mobility should be supported?
- Careful selection of the measurement antennas is mandatory. The choice is influenced by the system design aspects under investigation (e.g., beamforming or space diversity schemes usually require different antenna element spacing, polarimetric antennas have to be used if necessary) and the desired approach for the channel simulation. Here, the direct application of measured impulse responses and the impulse response synthesis based on the method of measurement based parametric channel modeling (MBPCM) [10] can be distinguished. The straightforward former approach computes the channel coefficients directly from the measured impulse responses by some simple preprocessing operations. Although this approach is considered to be reliable in all cases, it lacks flexibility, because the characteristics of the measurement antennas

is always part of the simulated system. Hence, antenna array geometry and element beam pattern of the measurement device must be suitable for a potential system application. Not every measurement antenna meets this requirement, because they are mainly designed to achieve a high resolution for spatial propagation parameter estimation. This is in turn the prerequisite for the very flexible MBPCM method which enables the synthesis of impulse responses also for different antenna array shapes than that of the measurement array. This is especially interesting if the influence of the antenna architecture itself has to be investigated for a system design.

- The result of link-level simulations are usually mean BER's averaged over a certain number of statistical realizations of the radio channel. When measured channel data is used for simulation, a careful analysis of the measured data is necessary for the result evaluation. Averaging over channels which are too different must be avoided. Instead, a closer inspection of the simulation results is required and a reasonable classification of the measurement data has to be attempted. Here, the parametric analysis is very valuable, since it enables to make a matching between the physical propagation conditions and the performance of a certain receiver configuration.

2.4 System-Level Simulations

The focus of system-level simulations is to obtain performance figures such as the distribution of the SINR or the bit error rate, and the outage probability for a particular network (system) layout of interest [2]. Therefore, a large number of random spatial distributions of the users are considered. The evaluation of interference scenarios plays the dominating role. The possible interference scenarios depend on the cell design, the frequency reuse, the user distribution, hand-over strategies, etc. Multi-dimensional channel sounding data offer the possibility to a realistic and yet effective way for system-level performance evaluation with a large degree of flexibility.

A measurement campaign with the objective of system-level simulations has always to consider two different interference scenarios/setups - the uplink and the downlink case. Fig. 1 addresses the interference scenario for the uplink transmission (a) as well as for the downlink (b) in a hypothetic cellular network with a frequency reuse factor of 1. In (a) the desired user (MS_D) is served by the base station (BS_A), which controls the user's transmit power adaptively. The co-channel users within the sectors B_x are in turn power controlled by their own base station BS_B . Their transmit signals produce co-channel interference (CCI) at the BS_A . For the downlink transmission (b) the MS_D is again served by BS_A , but here the CCI arises at the MS_D by the transmission from the BS_B serving a co-channel user in sector B_2 .

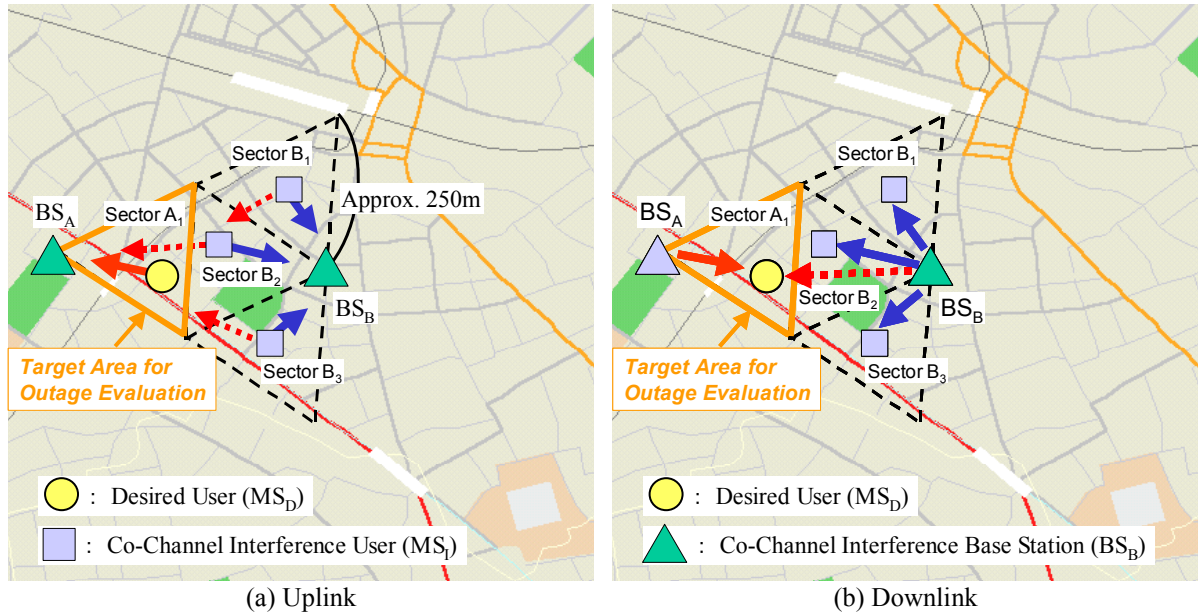


Fig. 1 User constellation and measurement setup for system-level simulations

The required channel measurements for the uplink case can be performed successively. A configuration of a channel sounder with one transmitter and one array receiver is sufficient to gather data for this system-level scenario. As an example, in Fig. 1 (a) the channel sounder is placed at the position BS_A and the mobile transmitter MS_D successively passes through different positions within the sector A_1 and the interferer sectors B_x . During the offline system-level simulation signals from the various positions of the desired user and the co-channel users can be summed in any random combination. The SINR at BS_A results from superimposing a simple statistical path loss model on the measured CCI impulse responses. The downlink case in Fig. 1 (b) is more complicated, but here the desired signal and the interferer signal can be measured within one measurement run. Two array receivers of a channel sounder and one transmitter are necessary for this configuration. At each base station (BS_A and BS_B) one array receiver is located. The mobile transmitter (MS_D) visits every desired measurement point within the target area. In the offline simulation, the signal from BS_B serving a user in sector B_2 acts as interference to be added to the desired signal at the MS_D , originating from BS_A . The SINR at MS_D results directly from the measured impulse responses without the need for superimposing a path loss model.

Measurement antennas for system-level simulations should consider the requirements of the focus system application. For cellular communication (including sector concepts) and WLAN scenarios the base station could for instance be equipped with ULAs and the mobile user with single element antennas or regular (or irregular) arrays, both with omnidirectional coverage.

3 Measurement Examples

A large number of measurement campaigns has been performed on different occasions by our research group together with partners in multiple projects covering many of the enumerated aspects. This section presents an overview on five different scenarios. More detailed documentation and some sample data can be found at www.channelsounder.de.

All measurement data have been gathered at a carrier frequency of 5.2 GHz with a bandwidth of 120 MHz. If not stated otherwise a transmit power of 27 dBm has been applied.

Measurement scenario 1 represents a suburban propagation environment [4]. The SIMO measurements took place in a hilly residential area in Ilmenau with several two-storied detached houses. The RX position was fixed with the array (uniform linear array with 8 elements) being directed downward toward a street. The TX trolley was equipped with an omnidirectional antenna and moved with approx 10 km/h on this street. Due to shading from several houses along the street mostly NLOS propagation was present during the measurement run. The sample data include 4 blocks of 20 consecutive snapshots from different sections of the measurement run.

The second scenario is a courtyard scenario at the Ilmenau Technical University. It is approx. 27 m x 26 m in dimension, surrounded by three-storied buildings at three sides and open at one side. Inside the yard several trees and other smaller obstacles (e.g. a metallic sculpture) are present. Due to the dimensions of the yard this propagation environment can be characterized as pico cell. The sample MIMO data cover a situation with fixed RX and moved TX, both equipped with polarimetric antennas [5]. The RX array (dual-polarized uniform circular patch array with 24 elements) has been placed at the centre of the open side of the yard at a height of about 2 m. The trolley with the transmit antenna (dual-polarized omnidirectional antenna) was moved with very low speed, completely under LOS. The TX antenna was mounted at about 2.5 m height on the trolley. A transmit power of 33 dBm has been applied. In [5] the performance advantage of joint polarimetric parameter estimation could be demonstrated with these data.

Measurement example 3 represents an intended access point scenario in a micro cell environment. The SIMO measurements took place in the vicinity of a bridge over a motorway. The RX array (8x8 uniform rectangular array) was mounted on the bridge about 7 m above ground and directed toward a motorway lane. This way, both the azimuth and elevation channel characteristics have been captured at the receiver site. A car with an omnidirectional antenna mounted on its roof (about 2 m above ground) has been used as mobile station (transmitter). Throughout the measurements a transmit power of 33 dBm has been applied. The car was moved at slow driving speed permanently under LOS. As soon as the car has passed the bridge, NLOS propagation arose.

Scenario 4 is a closed courtyard at the Ilmenau Technical University. It is shaped irregularly hexagonal with large metallic objects (e.g. transformers) inside. Due to its extended dimensions compared to the courtyard from example 2 this scenario can be characterized as micro cell. For the MIMO measurements the RX array (uniform linear array with 8 elements) was located at a fixed position outside the yard at a height of 1.2 m and has been directed toward a small passage to the inner courtyard. The TX array (uniform circular array with 16 elements) was mounted on a trolley at about 1.2 m height. The trolley was located inside the yard and has been moved with walking speed toward the passage. The sample data cover a small section of approx. 2 seconds duration, corresponding to about 2.7 m moving distance. For this section non-line-of-sight propagation between TX and RX was ensured.

Example 5 offers data from a measurement campaign performed in an industrial indoor environment [4], [6]. The measurements took place in a large aircraft hangar of Daimler-Chrysler Aerospace AG (DASA) in Hamburg/Germany. Inside the hangar several aircrafts as well as many metallic objects like scaffoldings and large transportation devices were present. The RX array (uniform linear array with 8 elements) was placed on an aisle in about 6 m height above ground with good view into the hangar. The omnidirectional TX antenna has been mounted on a trolley. The trolley was moved at walking speed in-

side the hangar. The sample data cover a small section of a measurement run with transition from NLOS propagation, caused by shading from an aircraft, to LOS.

Table 1 Summary of the presented measurement scenarios

Scenario	Cell type	TX / RX separation	TX RX antenna		Propagation
Suburban (Outdoor)	Micro cell	100 ... 150 m	Omni	ULA-8	NLOS
Small court yard (Outdoor)	Pico cell	20 ... 25 m	Pol.-Omni	Pol.-UCPA-24	LOS
Bridge over Motorway (Outdoor)	Micro cell	< 200 m	Omni	URA 8x8	LOS
Large court yard (Outdoor)	Micro cell	approx. 50 m	UCA-16	ULA-8	NLOS
Aircraft hangar / Industry (Indoor)	Pico cell	<150 m	Omni	ULA-8	NLOS → LOS

Omni: omnidirectional transmit antenna
 ULA-8: uniform linear array with 8 elements
 Pol.-Omni: dual-polarized antenna (horizontal / vertical) with omnidirectional characteristics
 Pol.-UCPA-24: polarization-sensitive uniform circular patch array with 24 elements
 URA 8x8: uniform rectangular array with 8 rows and 8 columns
 UCA-16: uniform circular array with 16 elements

4 Conclusions

Channel sounder measurements are important for propagation modeling and the evaluation of concepts for new wireless systems on different levels. Setting up a measurement campaign requires careful preparation and in advance considerations of the aspects of a system under investigation. Particularly, the selection of the measurement antennas needs to be matched to the intended use of the data. Documented example measurement data are provided at www.channelsounder.de in order to demonstrate the benefits of the measurement based channel modeling.

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