MIMO CHANNEL SOUNDING
AND DOUBLE-DIRECTIONAL MODELLING

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Abstract
In this paper a parametric measurement approach for double-directional modelling of radio channels is introduced. It is based on a broadband real-time MIMO (multiple-input multiple-output) channel sounder which uses multiple antennas at both the transmitter and receiver site. A subsequent super-resolution estimation step determines the polarisation resolved path weights, the delay and Doppler shift and the propagation directions of significant paths at both ends of the wireless link simultaneously. From the estimated parameter sets a local reconstruction of the multidimensional wave field in the extrapolated aperture domains of time, frequency and space is possible. This way the measurement device and antenna properties can be excluded from the channel (within well defined limits). As a result, the influence of a variety of application specific array architectures can be investigated with the reconstructed wave field. This builds the basis for manifold analyses and simulations of MIMO transmission links in a very realistic way.

Introduction
Multiple-input multiple-output (MIMO) radio channel access based on dual antenna arrays at both the mobile station (MS) as well as the base station (BS) is considered to be the ultimate means to increase the available capacity for high bit rate wireless links. By this technique the spatial diversity of multi-path channels in a rich scattering environment is optimally exploited and thus, highest data rates per user and an improved coverage and link quality can be expected. For the design, simulation and performance evaluation of MIMO space-time adaptive links, realistic spatial channel models are required which satisfactorily reproduce the physical process of wave propagation. Moreover, when considering complicated time-variant radio environments like industrial or road traffic scenarios, double-directional measurements combined with multidimensional high-resolution parameter estimation methods seem inevitable in order to get a sufficient resolution of the radio propagation channel. Whereas the concept of double directional channel modelling is extensively described in [1], first measurements of this kind were presented in [2], [3] and have been conducted in order to get more evidence of the double-directional channel concept. Recent channel sounding activities reported by several groups were mainly driven by the interest in evaluating the capacity of MIMO channels. The presented results where more or less restricted to the flat fading case and time-invariance assumptions. E.g. virtual arrays are used at transmitter or receiver site for simplicity and hence a static channel has to be presumed [4], [5], [6]. On the other hand, when using physical arrays at both ends of the wireless link, fast antenna multiplexing and broadband channel sounding, it becomes possible to analyse the time-variant MIMO channel matrix simultaneously in the time-delay-, frequency- and spatial domains. First results for joint superresolution estimation of the channel parameters based on the multidimensional ESPRIT including DOA, DOD, TDOA and Doppler have been reported in [10], [11].

Our work presented in the paper is motivated by the recent progress in wideband MIMO channel measurements and aims at highest measurement resolution in terms of the multidimensional ray-optical description of the MIMO channel. Based on a deterministic double-directional parametric model which is identified from measurement by superresolution procedures we intend to reconstruct
the local electromagnetic wave field in the vicinity of the measurement arrays. This leads to parametric double directional channel modelling based on measured data as introduced in [12].

**MIMO Channel Sounding**

For the MIMO measurements presented in this paper the wideband vector channel sounder RUSK ATM [7], [8], [9] has been used, which operates at 5.2 GHz and allows real-time measurements of the complex channel impulse response with a bandwidth of 120 MHz. The measurement device relies on periodic multi-frequency excitation signals, real-time sampling, and correlation processing. Since the recorded signal vector consists of integer periods of the received excitation signal response, it can be transformed to the frequency domain by FFT processing. The vector channel sounder measurement results can then be directly interpreted as a time-dependent sequence of the channel frequency response estimates. A 2-dimensional Fourier transform yields the joint Doppler/delay resolved impulse response.

In order to establish the MIMO capability of the sounder, a simultaneous multiplexing of the transmit and receive antennas is applied. Timing and switching frame synchronization between RX and TX is achieved during an initial synchronisation process prior to measurement data recording and is maintained over the complete measurement time by rubidium reference oscillators at both RX and TX. For real-time recording it is important to meet the Nyquist criterion which results from the Doppler bandwidth. This gives not only the possibility to reproduce the small-scale fading of the path weights. It allows also to "phase align" the sequentially recorded antenna array output which compensates for a Doppler shift dependent phase difference between antenna outputs in order to avoid DOA/DOD estimation errors of time varying paths.

An important aspect that needs to be considered for the measurements is the choice of proper antenna array architectures in order to resolve the directional structure of the multiple propagating waves. Hereby the antenna array design mainly determines the superresolution algorithm which can be applied and the resolved spatial dimensions. Regular planar array structures (i.e. uniform linear arrays (ULA) or uniform rectangular arrays (URA)) can be used for 1-D (azimuth) and 2-D (azimuth/elevation) resolution, respectively. These require antenna elements with some directionally selective characteristic in order to remove the inherent front/back ambiguity of planar arrays. Moreover, a non-linear transformation from azimuth/elevation to the row/column element phase response is involved. This restricts the resolvable range to a sector of less than 180° (typically 120°). Therefore, linear or planar antennas are suited to represent the BS in a typical macrocellular scenario or in a cellular indoor environment with the BS antenna mounted at a wall.

In contrast, with circular antenna arrays the complete azimuthal range of 360° can be covered. Realizations are given by the uniform circular array (UCA), the uniform circular patch array (UCPA) and the circular uniform beam array (CUBA). If elevation is of interest, vertically stacked UCPA or even spherical patch arrays (SPA) are possible solutions. This kind of antennas is suited to play the part of the mobile station in cellular environments. Dual circular antennas at both sides of the link are required to represent an adhoc network with no dedicated BS.

**Channel Parameter Estimation**

For extraction of the multipath parameters from the measurement results we assume a finite sum of discrete, locally planar waves, i.e. the wave fronts along the aperture of the receiving and transmitting antennas are presumed to be planar. It is further assumed that the relative bandwidth is small enough so that the time delay of the impinging waves simply transforms to a phase shift between individual antennas of the arrays, and the array aperture is small enough that there is no observable magnitude variation of any single wave received at different array elements. Furthermore, the time delay of arrival (TDOA) of the dominant wave-fronts, its Doppler shift, direction of arrival (DOA) at the receiver, and the direction of departure (DOD) at the transmitter (both in terms of azimuth and elevation) are presumed to be time-invariant during a measurement snapshot time interval, which is used to estimate one set of channel parameters.
The resulting K-multidimensional harmonic retrieval problem can be solved using a parameter estimation procedure based on the ESPRIT algorithm. This algorithm is a search-free method based on singular value decomposition of the signal space and is widely used for direction of arrival estimation. The algorithm can be considered as a superresolution algorithm since it results in parameter resolution, which may be much better than the Fourier resolution given by the maximum channel response vector snapshot time length, the measurement bandwidth, and the finite array aperture. The achievable resolution is only limited in terms of SNR, incorrect model assumptions, limited measurement accuracy such as remaining calibration errors, etc. Because of its computational efficiency, the unitary ESPRIT algorithm has been chosen for joint multidimensional channel parameter estimation. Although the efficiency of the multidimensional unitary ESPRIT algorithm is very well recognised, the higher flexibility of EM-algorithms for parameter estimation may be of advantage, especially in case of antenna arrays which show no shift invariant substructures. It should be noticed that in the special case of CUBA a transformation to a shift invariant structure is still possible which allows an error free application of the ESRIT.

**Parametric Channel Modeling**

Modelling of the mobile radio channel and link-level simulation is essential for the development of new mobile radio systems, since this allows to assess the benefits of different modulation, channel coding, multiple access and signal processing techniques in order to improve the performance of those systems. Statistical channel models attempt to reproduce certain channel characteristics observed from propagation measurements by statistical means and have been widely studied in recent years. In contrast, deterministic models (e.g. ray tracing models) try to give a more or less detailed reproduction of the actual physical wave propagation process for a given environment. They are based on geometric optics and model the wave propagation phenomena in a continuum of reflecting, diffracting and scattering objects by a superposition of plane waves. The accuracy of the ray tracing method is controlled by the number of rays used. However, from a practical point of view the high computational burden, the necessity of detailed site-specific geometric information, and the required knowledge about the reflection coefficients of the scattering or reflecting objects make ray tracing models difficult to use.

These limitations can be avoided if the underlying deterministic plane wave model from ray tracing is applied to measurement-based parametric channel modelling. Here, the role of the radio environment database is played by a collection of real-time measurement data in various typical radio environments. A deterministic characterisation of the radio channel becomes available when the individual multipath parameters are identified precisely. This is envisaged by multidimensional wideband MIMO measurements combined with superresolution channel parameter estimation. Thereby we can state that with an increasing resolution in terms of the individual parameters as well as with respect to the number of resolved parameters, the individual path weights can be considered as being time-invariant for a short-time measurement sequence, while the deterministic time variation of the path weight phases is contained in the Doppler shift parameter. This reveals that with a high multidimensional resolution the measurement data model approaches the deterministic data model of ray tracing.

Based on the estimated sets of multipath parameters that describe the discrete path model, we are now able to locally reconstruct the electromagnetic wave field in a distinct vicinity of RX and/or TX antennas. Superresolution hereby means that the approximated aperture area in general may be larger than the measured aperture. In a similar sense, the observed measurement bandwidth and the recorded window in time can be extrapolated. Parametric channel modelling leads not only to a substantial reduction of the data amount compared to the measurement data. The method of electromagnetic field reconstruction based on identified parameters helps to exclude the characteristics of the measurement antennas from the channel. Therefore, the influence of a variety of array architectures can now be simulated using only a single measured CRVS. That is, for a generic measurement record taken in some radio environment using a properly chosen measurement antenna, array impulse responses for different antenna array architectures can be generated. Moreover, statistic ensembles of impulse responses to be used for link-level simulations can be created artificially. Remembering that the carrier
wavelength is much smaller than the extrapolated array dimension, some "virtual movement of the mobile station" can be introduced that is superimposed on the MS trajectory covered during recording the measured data. It turns out that this way both, large-scale variations (inherently included due to the geometry of the scenario) as well as small-scale variations (due to 'animation of the model') are taken into account. Hence, this will result in a very realistic reproduction of the fading processes that can be incorporated in the simulations. In summary, with this measurement based parametric channel modeling approach, realistic link-level simulations based on measured channels as reported in [13], [14] would gain much more flexibility and significance.

References


