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 broadband real-time MIMO (multiple-input multiple-output) channel sounding measurements which use multiple antennas at both the transmitter and the receiver site. A subsequent super-resolution estimation step determines the polarisation resolved path weights, time-delay, Doppler shift and the propagation directions of the 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 vicinity of the measured aperture volume of time, frequency and space is possible. This way, the measurement antenna properties can be excluded from the channel. 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 a manifold of analyses and simulations of MIMO transmission links in a very realistic way.

INTRODUCTION

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 multipath channels in a rich scattering environment is optimally exploited. Several results have been published showing the MIMO capacity gain directly from measurements. Mostly, these results were based on virtual array application for simplicity and hence a static channel has to be presumed see e.g. [1], [2], [3]. On the other hand, for the design and performance evaluation of MIMO space-time adaptive links, we have to carry out link- and system-level simulations based on time-variant channel impulse response (CIR) data. With a broadband real-time MIMO channel sounder using physical arrays at both ends of the wireless link, it becomes possible to measure the time-variant MIMO channel matrix simultaneously in the time, frequency- and spatial domains. As demonstrated in [4], [5], these data can be directly used to predict the link- and system-level performance of various algorithms in a realistic environment. However, the flexibility of this method is restricted since only those antenna arrays that have been used during measurement can be assumed for simulation. Moreover, in general there is no ensemble of CIR realisations available that would be required for statistic BER estimation.

In this paper we describe a new measurement based parametric channel modelling (MBPCM) approach that overcomes these drawbacks. It is based on the double directional channel modelling idea extensively described in [6] and real-time measurements of this kind presented in [7], [8], [9]. The crucial point of MBPCM is to identify the propagation paths of a corresponding ray-optical data model by using high resolution multidimensional MIMO sounding techniques and adequate parameter estimation of dominant paths, e.g. as shown for joint super-resolution estimation of direction of arrival (DOA), direction of departure (DOD), time-delay of arrival (TDOA) and Doppler shift in [9], [10]. This leads to a parametric double directional channel modelling approach that excludes the antenna influence from the measured results and hence, allows to generate a variety of MIMO channel impulse response sequences from only a single measurement [11]. In this paper we summarise the main steps of the procedure that consists of MIMO measurement, parameter estimation and modelling.

REAL-TIME MIMO CHANNEL SOUNDING

For the MIMO measurements the broadband MIMO channel sounder RUSK ATM [8], [12] 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. 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 synchronisation between receiver (RX) and transmitter (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.

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. Antenna element design is mainly determined by requirements for bandwidth, uniform beam patterns, low inter-element coupling and polarisation resolution. On the other hand, the array design mainly determines the super-resolution algorithm which can be applied, the resulting accuracy and resolution as well as the resolvable spatial dimensions in terms of azimuth and elevation. 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 macro-cellular scenario or in a cellular indoor environment with the BS antenna mounted at a wall.

In contrast, with circular antenna arrays the complete azimuth range of 360° can be covered. Realisations 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 (MS) in cellular environments. Dual circular antennas at both sides of the link are required to represent an ad hoc 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. 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 TDOA, Doppler shift, DOA, and DOD parameters are presumed to be time-invariant during a measurement snapshot time interval, which is used to estimate one set of channel parameters. The resulting basic signal model in complex envelope notation is defined by

$$\mathbf{h}(\alpha,\tau,\psi_R,\vartheta_R,\psi_T,\vartheta_T)=\sum_{p=1}^{P}\boldsymbol{\gamma}_p\,\delta(\alpha-\alpha_p)\delta(\tau-\tau_p)\delta(\psi_R-\psi_{R_p})\delta(\vartheta_R-\vartheta_{R_p})\delta(\psi_T-\psi_{T_p})\delta(\vartheta_T-\vartheta_{T_p}) \qquad (1)$$

giving the complex multipath channel impulse response described by the P dominant paths and resolved in 6 dimensions for both directions seen from TX and RX, delay, and Doppler frequency shift. In (1) expression $\boldsymbol{\gamma}_p$ represents the 2x2 path weight matrix describing the two orthogonal polarisation responses of the RX and TX antennas, respectively, and the cross polarisation coupling. The DOA and the DOD are described by ψ_{Rp}, ϑ_{Rp} and ψ_{Tp}, ϑ_{Tp}, respectively for both azimuth and elevation. Presupposing appropriate antenna arrays at TX and RX site, the Fourier transform of the data model from (1) to the aperture space leads to

$$\mathbf{H}(t,f,n_R,m_R,n_T,m_T)=\sum_{p=1}^{P}\boldsymbol{\gamma}_p\cdot\mathrm{e}^{-\mathrm{j}2\pi\alpha_p t}\cdot\mathrm{e}^{-\mathrm{j}2\pi\tau_p f}\cdot\mathrm{e}^{-\mathrm{j}2\pi n_R\varphi_{R_p}}\cdot\mathrm{e}^{-\mathrm{j}2\pi m_R\theta_{R_p}}\cdot\mathrm{e}^{-\mathrm{j}2\pi n_T\varphi_{T_p}}\cdot\mathrm{e}^{-\mathrm{j}2\pi m_T\theta_{T_p}}\,. \qquad (2)$$

In the URA case the directional parameters transform as $\theta_p=\sin(\vartheta_p)$ and $\varphi_p=\cos(\psi_p)\cos(\vartheta_p)$. The variables m and n represent the spatial samples of the aperture domains at RX and TX antenna, respectively. The total measurement aperture volume size is given by $TBM_RN_RM_TN_T$ with the number of measured snapshots T, bandwidth B, and array size MN for both transmitter and receiver respectively. From this data volume, the parameter set $\{\alpha_p,\tau_p,\theta_{RP},\varphi_{RP},\theta_{TP},\varphi_{TP}\}$ has to be estimated by solving a 6-dimensional harmonic retrieval problem. Here the ESPRIT algorithm has been used. Based upon this, the $\boldsymbol{\gamma}_p$ are estimated by a least mean square procedure. The ESPRIT is a search-free method based on singular value decomposition of the signal space and is widely used for direction of arrival estimation. It offers super-resolution performance since parameter resolution may be much better than the Fourier resolution given by the finite size of the measurement aperture volume. 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. Special considerations are also required to handle coherent paths that always may occur in a multipath environment. In case of the ESPRIT application, the total data volume has to be subdivided in order to get a manifold of independent data sets. Although these sets may be overlapping, the resulting volume size is reduced and thus resolution is decreased.

PARAMETRIC CHANNEL MODELING

Presupposing that the individual multipath parameters are identified precisely, the estimated parameter set $\left\{\gamma_p, \alpha_p, \tau_p, \theta_{RP}, \varphi_{RP}, \theta_{TP}, \varphi_{TP}\right\}$ can now be considered as a deterministic double directional model of wave propagation which – similar to ray tracing – is based on geometric optics. The parameter set is now used to reconstruct the resulting electromagnetic wave field in a continuous spatial volume in the vicinity of the RX and TX antennas. Super-resolution 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. Within certain limits that are imposed by the inherent resolution and the directional coverage of the measurement antennas, the influence of both antennas is excluded from the result this way. As a result, the influence of a variety of array architectures can now be investigated using only a single measured CIR snapshot. In other words, for a generic measurement record taken in some radio environment using a properly chosen measurement antenna, array impulse responses for completely different antenna array architectures (i.e. varying arrangement, number and spacing of the elements) can be generated. Although this leads to a substantial reduction of data amount compared to the measurements, the geometry-based path statistics from the real environment is still exactly retained in the synthesised data.

The principle is illustrated in Fig. 1 for a measurement example taken in a road traffic scenario between two mobile platforms, each equipped with a circular uniform beam array [11]. From the estimated propagation paths (represented by the red and blue lines, respectively, that indicate the DOD / DOA angles as well as the TDOA, given by the line lengths) the resulting instantaneous interference patterns around the actual TX and RX positions are reconstructed. In the subsequent synthesis procedure channel response vector snapshots can now be generated for other specific antenna array arrangements (for example, ULA at the receiver and URA or UCA at transmitter site), dependent on the application under investigation.

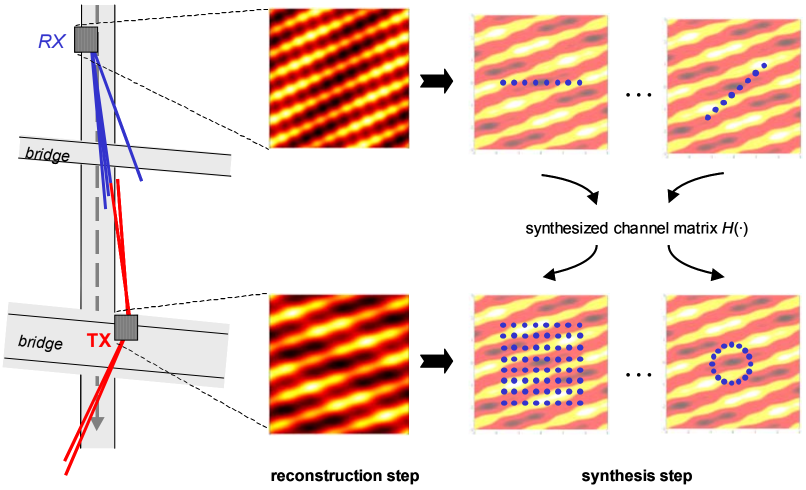

Fig 1: MIMO channel simulation based on parameter estimation, reconstruction of the electromagnetic wave field and antenna array output simulation

It is reasonable that this way also statistic ensembles of impulse responses can be provided to be used for link-level simulations. Remembering that the carrier wavelength is much smaller than the extrapolated array dimension, some "virtual movement of the mobile station" may 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. Compared to previous investigations based on measured channels (e.g. as reported in [4], [5]), realistic link-level simulations relying on the measurement based parametric channel modelling approach would gain much more flexibility and significance.

CONCLUSIONS

In this work we have introduced the concept of deterministic parametric channel modelling based on measured MIMO data. Using advanced MIMO radio vector channel sounding techniques for real-time measurements the channel model parameters describing the multidimensional wave propagation model can be resolved as accurately and generally as possible. Hereby the antenna array design mainly determines the super-resolution possibility and the resolved spatial dimensions. This leads not only to a substantial reduction of the data amount compared to the measurement data but also helps to remove the measurement antenna characteristics from the measurement result. This allows to simulate the corresponding output characteristic of specific application arrays and to investigate the influence of a variety of array architectures. That is, for a generic measurement record taken in some radio environment using a properly chosen measurement setup, array impulse responses for different antenna array architectures can be generated. Initial investigations have been carried out based on MIMO measurement data including first measurements between two mobile platforms. First results related to the modelling approach have been presented.

According to the basic philosophy of this modelling approach, it is desirable to have as much resolution power as possible during the analysis step in order to have a maximum number of degrees of freedom for the follow-up synthesis step. The array architecture for the synthesis step is application specific and typically has a lower complexity. As a result, future challenges include the further improvement of both the measurement setup as well as parameter estimation procedure in terms of accuracy and resolvable dimensions (e.g. elevation for TX and RX antennas, polarisation) in order to provide the complete description of the channel model. This has influence on the design of the antenna architectures in order to provide a maximum of coverage and resolved angular dimensions and to cover also polarisation. Moreover, the accuracy, resolution and flexibility of the parameter estimation procedure must follow these goals.

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