

# MIMO MEASUREMENT FOR DOUBLE-DIRECTIONAL CHANNEL MODELLING

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## Abstract

In this paper a parametric modelling approach for double-directional radio channels is introduced that is based on measured data. The MIMO (multiple-input multiple-output) measurement principle using multiple antennas at both the transmitter and receiver site can be effectively exploited to estimate the propagation direction, delay and Doppler shift of any significant path at both ends of the wireless link simultaneously. From the estimated parameter sets a precise reconstruction of the multidimensional wave field in the aperture domains of time, frequency and space is possible. Since this way the measurement antenna properties are excluded from the channel, the influence of a variety of other 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.

## I. 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 techniques the spatial diversity of multipath 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. For that purpose several theoretical, more or less simplified MIMO channel models have been proposed recently (e.g. [1],[2]). Moreover, when considering complicated time-variant radio environments like industrial or road traffic scenarios, double-directional measurements combined with high-resolution parameter estimation methods seem inevitable in order to get a high resolution of the radio propagation channel. First measurements of this kind were presented in [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 such channels (e.g. [4],[5],[6]). In many cases this has been achieved by employing virtual arrays at transmitter or receiver site and hence a stationary channel was assumed. On the other hand, when using physical arrays at both ends of the wireless link and broadband channel sounding it becomes possible to capture the time- and frequency-dependent MIMO channel matrix. This measurement principle has been extensively discussed in [7] and corresponding measurement results studying the time-variance of MIMO propagation channels have been given e.g. in [8],[9],[10].

Our work presented in this paper is also motivated by the recent progress in MIMO channel measurements and aims at highest measurement resolution in terms of parametric superresolution and in terms of the number of resolved parameters. Compared to conventional measurement approaches with non-directional or one-sided directional resolution (SISO – single-input single-output / SIMO – single-input multiple-output), this promises highest performance for channel parameter identification and will enable us to characterise the double-directional radio propagation channel in a deterministic way. This builds the basis for a parametric channel modelling approach where we intend to reconstruct the local electromagnetic wave field in the vicinity of the measurement arrays from the estimated channel parameters. Since with this approach the characteristics of the measurement antennas are practically excluded from the channel, the influence of several other array architectures can now be investigated using only a single measured channel response vector snapshot. In the same sense the measurement bandwidth and the observation window in time can be extrapolated.

The paper is organised as follows: The next section describes the MIMO measurement procedure and addresses the issue of proper antenna architectures for the measurements. Then in section III the parameter estimation procedure is explained that is used to derive sets of multipath parameters from the measurements. In the fourth section we introduce the concept of deterministic parametric channel modelling based on the estimated parameters and in section V measurement results between two mobile platforms are presented, both equipped with circular uniform beam arrays offering 360° azimuthal coverage. To our knowledge these are the first measurements of this kind and can be seen as a step toward the investigation of wave propagation in ad-hoc radio links between moving cars in a road traffic scenario. The last section gives a summary and outlines future challenges.

## II. MIMO channel sounding

For the MIMO measurements presented in this paper the wideband vector channel sounder RUSK ATM [11] 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  $H(t, f, m)$  with  $m = 1 \dots M$  as an aperture parameter that corresponds to the output of an antenna ( $M$ : total number of antennas). A 3-dimensional Fourier transform yields the joint Doppler/delay/angular resolved impulse response  $h(\alpha, \tau, \theta)$ .

In order to establish the MIMO capability of the sounder, the approved sequential acquisition principle at the receiver (RX) antenna [11] is extended by sequential emission of the periodic multi-frequency excitation signal from the multiple transmitter (TX) antennas. This requires simultaneous multiplexing of the transmit and receive antennas. 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. The total snapshot time length is now given by  $t_s = 2 \cdot \tau_{\max} \cdot M_{Tx} M_{Rx}$ , where  $M_{Tx}$  and  $M_{Rx}$  are the number of antennas at the TX and the RX site, respectively and  $\tau_{\max}$  represents the maximum path excess delay. The factor of two comes from the one blank period which is inserted at the receiver after every period acting as a guard interval to avoid switching transients. This all sets the limits on the maximum Doppler bandwidth to less than  $1/t_s$ . Due to the high measurement repetition rate of the sounder hardware and its long-term recording capability both small-scale fading of the path weights as well as long-term variations of the channel impulse response sequence are captured.

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 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 [7]. This restricts the resolvable range to a sector of less than  $180^\circ$  (typically  $120^\circ$ ). 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 (cf. case 1 in Fig. 1).

In contrast, with circular antenna arrays the complete azimuthal range of  $360^\circ$  can be covered. Realizations are given by the uniform circular array (UCA), the uniform circular patch array (UCPA), or the circular uniform beam array (CUBA). This kind of antennas is suited to play the part of the mobile station in cellular environments or when dual circular antennas are employed to represent an ad-hoc network with no dedicated BS (cf. case 2 in Fig. 1). The specific property of a CUBA is its circular arrangement of directive antennas (Fig. 2) which show no phase difference between these beams. Then the measured output can be directly interpreted as measured result in the beam space. This is obviously not the case for an UCPA where a phase difference between the directive antenna outputs cannot be avoided.

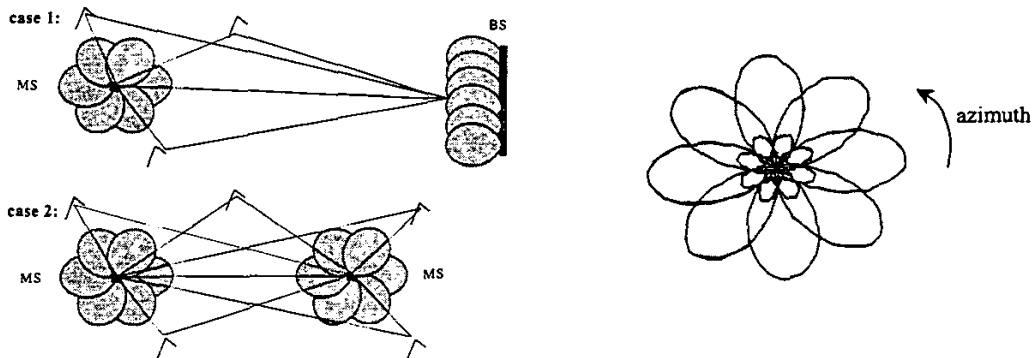


Fig. 1: Measurement antenna architectures dependent on the application scenario: Cellular (case 1) vs. ad-hoc scenario (case 2). Fig. 2: Geometric arrangement of the switched directive beams of a CUBA with 8 antenna elements

For estimation of the multipath parameters here we have in mind to use an ESPRIT-based algorithm [16], which however is restricted to arrays that exhibit so-called shift invariances. While planar arrays like ULA or URA are fulfilling this requirement, circular structures like UCA or SUCPA do not correspond to the ESPRIT in an ideal sense and therefore they will cause a systematic error. In case of the CUBA a Fourier transformation can be performed that maps the array

output into a virtual aperture space [14]. This transformed signal space contains the shift-invariance structure, therefore allowing the application of the ESPRIT and even spatial smoothing is possible for coherent source handling. Two identical prototypes of a CUBA consisting of a biconical horn antenna with a coaxial feeder and 8 directive elements have been designed for 5.2 GHz [12]. These two antennas have been employed throughout our measurements presented in section V.

### III. Data model and estimation of multipath parameters

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)  $\tau_p$  of the wave-front  $p$ , the Doppler shift  $\alpha_p$ , its 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 measurement time interval is given by the number of channel response vector snapshots. In complex envelope notation we can define the basic signal model as

$$\mathbf{h}(\alpha, \tau, \psi_R, \vartheta_R, \psi_T, \vartheta_T) = \sum_{p=1}^P \gamma_p \delta(\alpha - \alpha_p) \cdot \delta(\tau - \tau_p) \delta(\psi_R - \psi_{R,p}) \delta(\vartheta_R - \vartheta_{R,p}) \cdot \delta(\psi_T - \psi_{T,p}) \delta(\vartheta_T - \vartheta_{T,p}) \quad (1)$$

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  $\gamma_p$  represents the  $2 \times 2$  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  $\psi_{R,p}$ ,  $\vartheta_{R,p}$  and  $\psi_{T,p}$ ,  $\vartheta_{T,p}$ , respectively for both azimuth and elevation. In case of linear apertures these parameters contain a transformation in terms of a directional cosine [7]. Presupposing appropriate antenna arrays at TX and RX site, the transformation of the data model from (1) to the aperture space leads to [7]

$$\mathbf{H}(t, f, n_R, m_R, n_T, m_T) = \sum_{p=1}^P \gamma_p \cdot e^{-j2\pi\alpha_p t} \cdot e^{-j2\pi\tau_p f} \cdot e^{-j2\pi m_R \vartheta_{R,p}} \cdot e^{-j2\pi n_R \psi_{R,p}} \cdot e^{-j2\pi m_T \vartheta_{T,p}} \cdot e^{-j2\pi n_T \psi_{T,p}} \quad (2)$$

with the variables  $m$  and  $n$  representing the corresponding spatial aperture domains at RX and TX antenna, respectively. The resulting harmonic retrieval problem can be solved using a  $K$ -dimensional 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 [13] has been chosen for joint multidimensional channel parameter estimation, yielding the parameter sets  $\{\psi_p, \alpha_p, \tau_p, \theta_{RP}, \varphi_{RP}, \theta_{TP}, \varphi_{TP}\}$ .

### IV. Measurement-based parametric channel modelling

Modelling of the mobile radio channel 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 data base 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  $\gamma_p$  can be considered as being time-invariant for a short-time measurement sequence, while the deterministic time variation of the path 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  $\{\gamma_p, \alpha_p, \tau_p, \theta_{RP}, \varphi_{RP}, \theta_{TP}, \varphi_{TP}\}$  that describe the discrete path model, we are now able to locally reconstruct the electromagnetic wave field in a distinct vicinity of RX or TX antenna, in time or in frequency. Superresolution hereby means that the approximated aperture area is larger than the measured aperture. Since this method of field reconstruction helps to exclude the characteristics of the measurement antennas from the channel, the influence of a variety of other array architectures can now be simulated using only a single measured impulse response. Moreover, statistic ensembles of impulse responses to be used for specific 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" could 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. To summarize the modelling idea the scheme in Fig. 3 shows the way how to get from the measurement data to application-specific impulse responses to be used for simulations. Additionally, section V gives a measurement example to demonstrate the modelling principle as well.

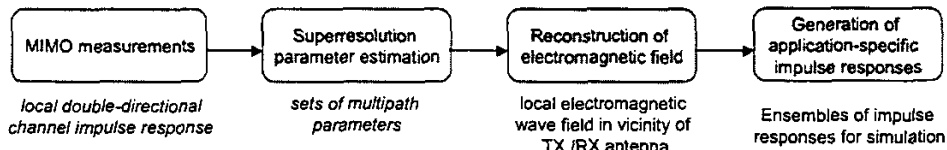


Fig. 3: Principle of parametric channel modelling based on high-resolution MIMO measurements

## V. Measurement results

In this section we will focus on a series of MIMO measurements with the RUSK ATM vector channel sounder where the radio wave propagation between two mobile platforms has been investigated. For this purpose two identically constructed prototypes of the circular uniform beam array (CUBA) have been employed at both transmitter as well as at receiver site. The TX and the RX antenna were mounted on the roof of a car each, thus enabling the investigation of the multipath propagation between both vehicles, each with an azimuthal coverage of  $360^\circ$ . This car-to-car propagation scenario with the two cars moving in road traffic corresponds to a mobile ad-hoc network architecture as it is discussed for 4G. To our knowledge these are the first real-time measurements of this kind that have been reported in the literature. The mobile-to-mobile measurements have been conducted in typical urban scenarios (living area, parking site) and in a road traffic scenario (freeway). In the following we will focus only on the 'road traffic scenario' shown in Fig. 4 and Fig. 6. For this measurement the TX car was placed on top of a bridge (freeway with heavy traffic). The RX car was moved with slow speed on a country road below the freeway. At first Fig. 5 shows an example for the measured beam-to-beam dependent impulse response, taken from a single snapshot at about 75 sec. during the measurement run. For each TX block (beam 1...8) the associated RX beams are depicted. Because of the directional nature of the CUBA a raw double directional analysis can be deduced from the picture already. For example, TX beams 7/8 and RX beams 1/2 approximately describe the LOS connection. Then the joint superresolution estimation of the directional channel parameters (DOD, DOA) [17], [8] and of the path delay has been carried out for the complete measurement run. This procedure relies on the CUBA-ESPRIT algorithm which has been included into the multidimensional joint estimation procedure to yield DOA and DOD. In Fig. 6 for each estimated discrete path of the complete measurement run the corresponding estimated delays are shown. It can be seen clearly that the RX car was moved toward the TX position (delays decreasing), then passed the bridge and moved away. It can also be seen that besides the direct path several more or less stable paths appear and disappear at certain instances of time.

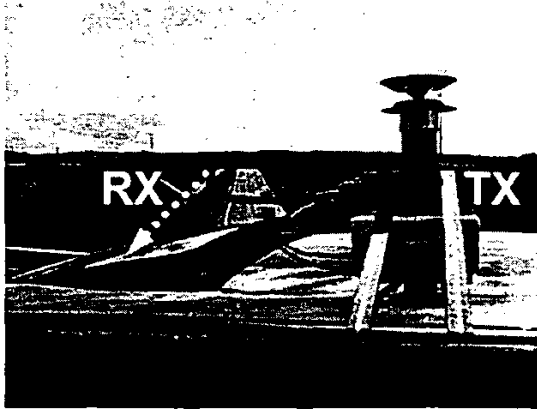


Fig. 4: Scenario 'road traffic' with TX on top of a bridge and RX on the street below, driving toward TX position. Both TX and RX are equipped with CUBA antennas.

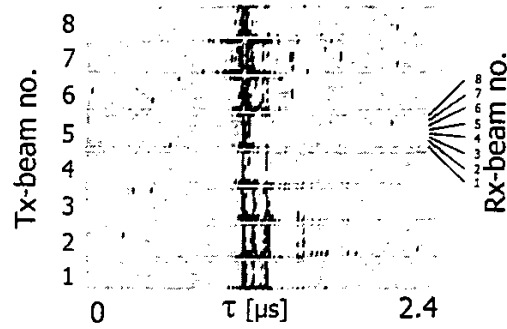


Fig 5: Beam-to-beam dependent impulse response for the mobile-to-mobile measurement with CUBAs at RX and TX

For the same snapshot taken before we have then used the parameter estimation result and reconstructed the electromagnetic wave field in the vicinity of the actual RX and TX position, based on the plane waves assumption. The result is shown in Fig. 7. For the four estimated propagation paths the DOD/DOA angles are indicated by the path line orientation and the line length represents the TDOA. The resulting instantaneous interference pattern is shown in the enlarged pictures for a region of  $(\pm 3 \lambda)$  around the actual RX and TX positions.

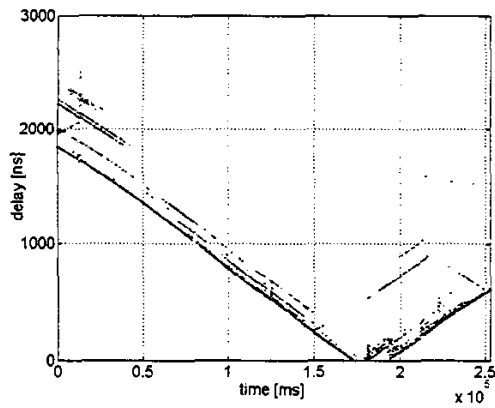


Fig. 6: Estimated discrete paths for the complete measurement run in the road traffic scenario with corresponding delays

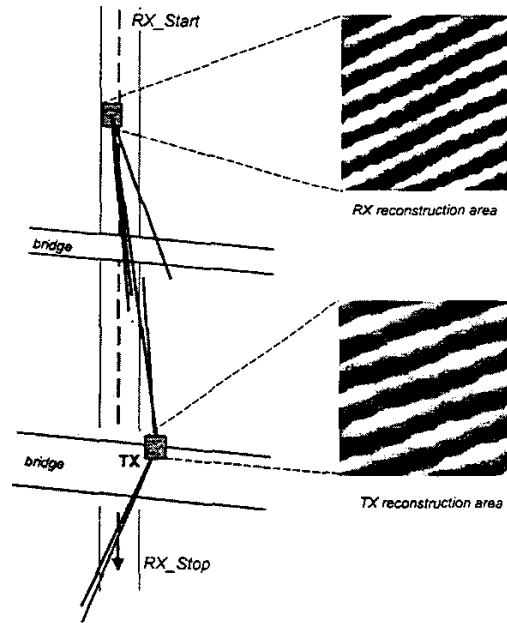


Fig. 7: Result of electromagnetic field reconstruction in the vicinity of the RX antenna  $(\pm 3 \lambda)$ , based on the plane wave assumption

Finally, Fig. 8 gives an example on how to exploit the reconstructed electromagnetic field for evaluation of completely different antenna array structures. For this purpose the characteristics of a Uniform Circular Array consisting of 16 omnidirectional antennas like shown in the left part of Fig. 8 has been adopted. For this array we have taken the reconstructed fields (i.e. from the measurements with the 8-element CUBA) at the required TX and RX positions and recalculated the impulse responses assuming also a bandwidth of 120 MHz. Due to the 16x16 transmit/receive antenna elements now a total of 256 channels results.

Comparing the measured beam-to-beam dependent impulse response for the CUBA-CUBA arrangement from Fig. 5 with the simulated impulse response for the UCA-UCA arrangement from Fig. 8 we will see some noteworthy distinctions

which result from the different antenna architectures. What is common for both antennas is the coverage of  $360^\circ$  in azimuth. However, severe differences between the individual beam responses of the CUBA could be observed. This results from the fundamental difference in the individual element responses which are directive in case of the CUBA (applied during the analysis / measurement step) and omnidirectional in case of the UCA (defined for the synthesis / modelling step). Of course, in terms of multipath propagation modelling, the maximum number of degrees of freedom is limited by the antenna array that is used during the measurement. That is, e.g. the maximum number of coherent paths contained within one delay bin, is limited by the CUBA array used during the measurement. Moreover, since the analysis is limited to the azimuth plane, the synthesis is limited in the same sense.

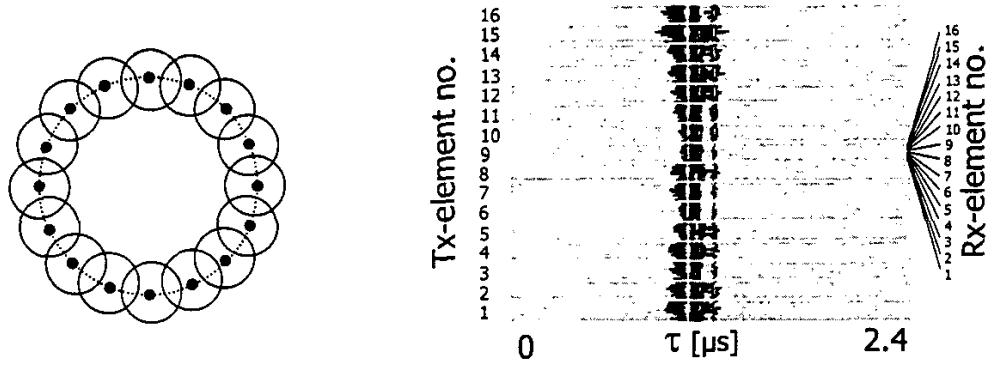


Fig. 8: Geometric arrangement of a UCA consisting of 16 omnidirectional antennas (left) and resulting spatial impulse response, calculated by placing UCAs in the reconstructed wave fields at TX as well as RX position (right)

## VI. Conclusions and Outlook

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 superresolution possibility and the resolved spatial dimensions. Whereas linear and planar antennas may be used to represent the base station, circular or spherical antennas are adequate to play the part of the mobile station. Compared to SIMO measurements, MIMO here offers the advantage of much higher resolution power to estimate the deterministic multipath model. This way even the characterisation of temporal changes of the model parameters (DOA, TDOA, DOD, path weights) for typical movements in a mobile radio environment is possible.

Based on the superresolution channel parameter estimation result the electromagnetic wave field in the vicinity of the array can be reconstructed. This leads not only to a substantial reduction of the data amount compared to the measurement data. Moreover, it 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.

Limitations of the discussed modelling approach currently can be seen in the following points:

- To achieve highest modelling precision the number of resolved dimensions must be sufficient. The example given relied on circular antennas. Therefore only the azimuthal characteristics has been measured. Further improvement is expected by capturing also the elevation properties.
- The influence of the directional characteristics of real antenna arrays, especially the characteristics of the individual array elements has to be examined carefully (including also the polarisation properties).
- The complexity of the model to be simulated (e.g. number of paths) is limited. It is determined by the number of paths resolved during the measurements. This number is limited by the size of the antenna arrays (multidimensional DOD / DOA angular resolution), the bandwidth (delay resolution) and observation window length (Doppler resolution).
- The quality of the modelling approach essentially depends on the accuracy of the measurements (for example, in terms of the dynamic range).

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.

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. The multidimensional SAGE (Space-Alternating-Generalized-Expectation-Maximization [15]) algorithm is subject of actual investigations.

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