SUPERRESOLUTION MEASUREMENT AND SIMULATION OF MOBILE VECTOR RADIO CHANNELS

R.S. Thomä[1], D. Hampicke[1], A. Richter[1], G. Sommerkorn[1], U. Trautwein[2]

[1]Department of Electrical Engineering and Information Technology
Ilmenau Technical University
P.O.B. 100565, D-98684 Ilmenau, Germany

Phone: (+49) 3677-692622, Fax: (+49) 3677-691113, E-mail: tho@e-technik.tu-ilmenau.de

[2]IMMS Inst. of Microelectronic and Mechatronic Systems
Langewiesener Str. 22, D-98693 Ilmenau

Abstract: For the simulation and design of smart antenna transmission principles in mobile radio, precise knowledge of the time-variant directional multipath structure in various radio environments is required. In this paper a new broadband multiple-input-multiple-output (MIMO) vector radio channel sounder is described which uses multiple antennas at the transmitter as well as at the receiver position. The proposed MIMO measurement principle can be effectively exploited to decorrelate multiple propagation paths and, thus, enhance resolution. With the multidimensional unitary ESPRIT-algorithm applied, joint superresolution estimation of the direction of departure (DOD), the time-delay of arrival (TDOA), and the direction of arrival (DOA) of the propagating waves becomes possible. The measured results can also be used directly for the simulation of combined transmit-receive diversity transmission principles and space-time (ST) adaptive receivers in a multiuser scenario. Results are referenced which are based on a measurement in a complicated indoor environment as it is typical for industrial WLAN applications.

1. Introduction

Space-time processing is considered to enhance system performance of 3G and 4G mobile radio systems. High performance systems will be able to use multiple antennas at both the receiver and the transmitter site. The expected benefits include increased capacity and well defined quality of service as a result of diversity gain, source separation, interference reduction, and joint space-time equalization. Proper design, simulation, and performance evaluation of ST adaptive processors, however, require profound knowledge of the radio channel impulse response (CIR) statistics. Although various modeling approaches have been developed, sophisticated measurement methods are definitely required not only to evaluate these models but also to produce CIR data which can be directly used for simulation in a realistic radio environment. Simulation based on measured data has been shown to be absolutely realistic w.r.t. the channel influence as long as the statistics of the time variant multipath propagation is completely reproduced. This requires a high measurement repetition rate and a long time record capability. Also the arrangement of the antenna arrays at the Tx and the Rx position is very important. For the direct simulation approach, it should exactly correspond to the simulated target transmission system. If channel modeling is more important, the antennas should be arranged in a way that channel model parameters can be deduced which describe the environment as accurately and as generally as possible.

2. Status of SIMO channel sounding

Broadband vector radio channel sounders are already well known for single-input-single-output (SISO) [2] and single-input-multiple-output (SIMO) measurements. In the latter case, a uniform linear antenna array (ULA) is typically used at the receiver that plays the role of the base station [1]. The measurement devices rely on periodic multifrequency excitation signals, realtime sampling and correlation processing. The highest possible measurement repetition rate for a channel with a maximum path excess delay $\tau_{\max}$, is $1/\tau_{\max}$. Its lower limit is given by the Doppler bandwidth B_{max} which determines the Nyquist sampling frequency of the fast fading CIR taps. Since the delay-Doppler spreading factor $S = \tau_{\max} B_{\max}$ of typical mobile radio channels is well below 1%, fast sequential acquisition of the antenna outputs is possible for realtime recording of the SIMO – CIR in case of reasonable array dimensions [3]. Superresolution of the parameter sets (τ_p, θ_p) which describe the path TDOA and

DOA, is achieved by the subspace and least squares based 2D unitary ESPRIT algorithm [4]. Subsequently, the sequence of the instantaneous path weights are estimated by a least squares solution from the time-variant SIMO – channel response data snapshots. Obviously, the angular resolution of SIMO channel sounding is limited to DOA at the Rx only. But the beam pattern of the Tx antenna strongly influences the result. Omnidirectional antennas are typically used at the Tx.

Finally, it has been shown that precise device calibration is required in order to actually achieve the desired superresolution gain especially for coherent paths. That is most important in order to reduce the influence of the mutual antenna element coupling [6], [7]. A multipath environment has to be considered as coherent if the paths can not be resolved within the limits given by the inverse of the measurement bandwidth and array size, respectively. On the other hand, path decorrelation is required in order to enhance the rank of the data matrix which is a prerequisite for resolution. If the parameters are to be estimated from only one single instantaneous snapshot in time (or if the environment is partly static) the only way to achieve spatial path decorrelation at the receiver array is subarray smoothing. However, if two paths are closely spaced in azimuth, the spatial correlation period may be much larger than the available Rx array dimension. This strongly decreases the efficiency of that procedure. Therefore, even in the case of very small calibration errors, the resolution is severely limited.

3. MIMO Channel Sounding

The stated limitations of SIMO channel sounding may be overcome by a very simple conceptional step. It consists of extending the sequential acquisition at the Rx by including sequential emission of the periodic excitation signal from multiple Tx antennas as well. Fig. 1 gives an idea of the setup. Synchronous switching at the Rx and the Tx requires initial timing and switching frame synchronization which has to be maintained over the complete measurement time. Although the total snapshot time length now is roughly given by $2\tau_{\max} M_{Tx} M_{Rx}$, with the Number of the antennas M_{Tx} and M_{Rx} at the Tx and the Rx site, respectively, the proposed limit given by the channel spreading factor may still be satisfied (e.g. for $M_{Tx} = 4$ and $M_{Rx} = 8$). Otherwise, only a small penalty on the Doppler bandwidth shows up.

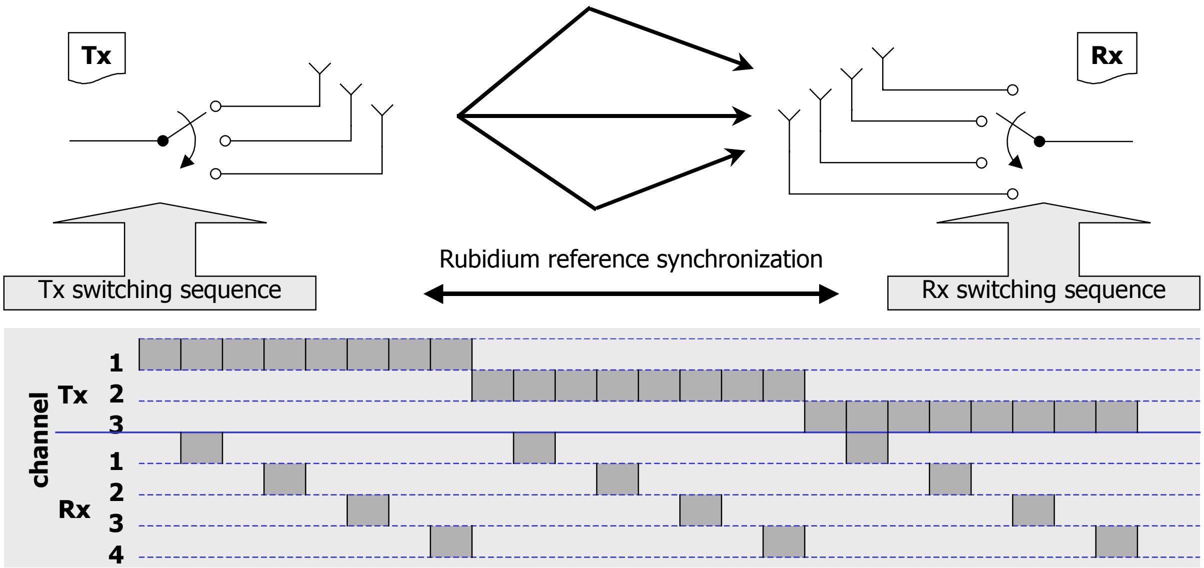

Fig 1. Basic principle of sequential MIMO channel sounding.

The advantage of the MIMO structure is manifold. At first, during measurement data acquisition some spatial-time diversity is introduced which supports path decorrelation at the Rx without any Tx movement and, thus, enhances resolution of closely separated coherent paths. In the same way, direct usage of the data allows investigation of combined transmit-receive diversity and space-time coding schemes which are considered to be strong candidates for system capacity enhancements [10]. Also DOD superresolution is becoming feasible, but for this application further design considerations regarding the Tx array arrangement are required. A very effective solution is given in the next chapter.

4. Joint DOD/TDOA/DOA Estimation

For a more complete description of the channel multipath structure not only the TDOA and the DOA at the receiver but also the DOD of the waves emitted from the transmitter is required. With the narrowband, plane waveform model it has been shown in [9] that the channel response in the Doppler-DOA-DOD variant impulse response domain (α, τ, θ, φ) is related to the space-time variant frequency domain (*t, f, s, l*) by a multidimensional Fourier transform relation:

$$\alpha, \tau, \theta, \varphi \quad h(\alpha,\tau,\theta,\varphi)=\sum_{p=1}^{P}\Gamma_k(\alpha)*\delta(\alpha-\alpha_p)\,\delta(\tau-\tau_p)\delta(\theta-\theta_p)\,\delta(\varphi-\varphi_p)$$

$$t, f, s, l \quad H(t,f,s,l)=\sum_{p=1}^{P}\gamma_k(t)\mathrm{e}^{-\mathrm{j}2\pi t\alpha_p}\mathrm{e}^{-\mathrm{j}2\pi f\tau_p}\mathrm{e}^{-\mathrm{j}2\pi s\theta_p}\mathrm{e}^{-\mathrm{j}2\pi l\varphi_p}$$

Therefore, the estimation of the discrete wave propagation parameters can be considered as a multidimensional harmonic retrieval problem. E.g. if no Doppler resolution is intended, a 3-D ESPRIT algorithm is required to solve for the remaining parameters (τ_p, θ_p, φ_p) which are described in Fig. 2. Otherwise the 4-D ESPRIT must be used.

From the MIMO channel sounding point of view, the discrete wave propagation model as described above depends on a proper Rx and Tx antenna architecture and the respective definition of spatial domains *s* and *l*. A linear uniform array (ULA) seems very reasonable at the place of the Rx site and a simple transformation $\theta = \sin(\theta')$ is included. At the Tx an antenna aperture with 360° coverage in azimuth seems more appropriate since it represents the mobile station (MS). In [9] we proposed to use a circular uniform beam array (CUBA). The advantage is a very compact design since it may consist of only one single antenna which acts as a switched beam antenna as indicated in Fig. 2. If it is used in place of the Tx array in Fig. 1, the switch directly selects the circular shifted beams which are indicated in Fig 2. With a Fourier transform of this sequence we end up in a virtual aperture domain *l* where the basic shift invariance relation which is required for the ESPRIT calculation, can be defined.

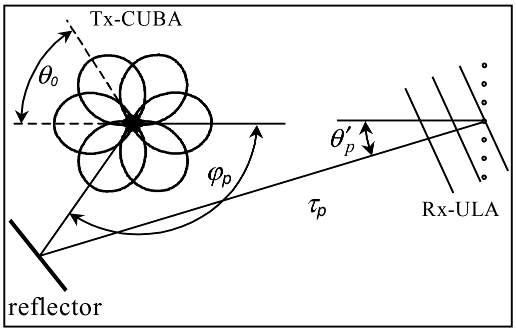

Fig 2. Discrete DOD-TDOA-DOA model of wave propagation

The MIMO based joint estimation of the double directional channel model in Fig. 2 allows a very precise description of the wave propagation independent from the individual antennas used. In its generality, the results can be compared e.g. to ray tracing models. Note that the proposed model can easily be extended to include elevation and polarization as well.

5. Multiuser SIMO-Simulation

In the design flow of wireless systems it is very important to assess the link performance in a realistic radio environment. Most often, simulation is based on statistical channel models with idealized conditions such as uncorrelated scattering, perfect tap timing, and delay window synchronization of the receiver. Therefore, the estimated performance figures may be far away of what can be expected in real life. That is even more true if the performance in a multiuser scenario is concerned which causes cochannel interference. On the other hand, a performance test based on a demonstrator tends not only to be very expensive, but in general it will be limited by restrictions in flexibility and availability since the variety of different factors of impact cannot be tested due to expensive hardware and realtime software manipulations. Simulation based on the measured CIR sequences, however, can be much more flexible and informative since the variety of different ST processor principles (e.g. whether it is linear or nonlinear, fractionally or symbol spaced), the tap adaptation rules, the complexity (number of spatial and temporal taps), the timing and synchronization mechanisms, etc. can be tested.

In order to simulate a multiuser scenario, some kind of MIMO measurement is again required. However, it seems not to be feasible to use the setup described in Fig 1 for that purpose since the multiple inputs that correspond to the different users are to be spread out randomly in the whole radio cell. On the other hand, the strict realtime input channel synchronization which is required for DOD estimation as described above, may be released in this case. Then the channel inputs which correspond to the multiple users can simply be taken from consecutive measurements at different locations of the Tx antenna. In [8], a simulation of an adaptive ST processor in an industrial environment based on real-time CIR measurements has been reported. The simulation setup is given in Fig. 3., the radio channel has been analyzed in [5]. The simulation results given in [8] show very impressively how the performance of a ST processor for equalization and cochannel interference reduction depends on its complexity.

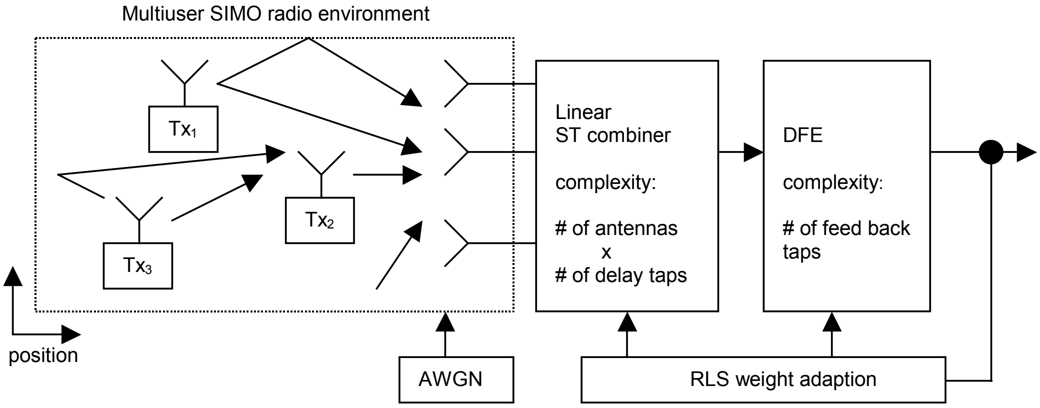

Fig. 3. Principle of Multiuser SIMO measurement and simulation

5. Conclusions

The well known SIMO vector radio channel sounder principle can be extended to MIMO measurements. The advantage is the enhanced parameter resolution by improved path decorrelation and additional direction of departure estimation. The measured results can also be used for realistic simulation of adaptive space-time processors in a multiuser environment.

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