Double-directional radio channel estimation at 2GHz for high speed vehicular mobiles - Experimental results

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Abstract

Results obtained from a high speed outdoor field trial in the 2GHz band are presented. The aim of this contribution is to characterize double directional radio propagation apt for MIMO (Multiple Input Multiple Output) systems in quite an unusual environment. From the Wideband measurements we estimate the delays, arrival and departure angles using two multiplexed antenna arrays, one circular and one linear. The measurement results show a dominant LOS component and low angular spread for both, DoAs and DoDs, allowing to anticipate only limited diversity gain.

Keywords

MIMO measurements, high-speed, wideband, circular array, DoA and DoD estimation, array cross multiplexing.

1. Introduction

Multiple-Input Multiple-Output (MIMO) systems have raised quite some interest recently through their ability to transport high data-rates in rich scattering environments [1, 2]. While the former work mainly focused on (Monte-Carlo) simulations of the offered capacity in a random, independently Rayleigh-fading channel [9], the performance of systems operating in a real-world environment can only be assessed with appropriate measurements. While the assumption of rich scattering allowed statistical evaluations culminating in high capacity [7], this assumption cannot be verified in many practical propagation environments [5]. Then, however, estimation of directions-of-arrival (DoAs) and directions-of-departure (DoDs) can be vital to achieve high gain with beamforming [3].

A suitable measurement technique and corresponding first measurement results for wideband MIMO channels were published in [8] where simultaneous multiplexing of transmit and receive antennas was used to capture a time- and frequency-dependent MIMO channel matrix. These data was then used to reveal the underlying double-directional behaviour of the channel. But also other groups had or have MIMO channel measurements running, one part focusing on MIMO channel capacity [4, 5] and the other on the double-directional propagation behind [10, 11]. This paper makes a contribution to the second, more general approach.

Driven by the expected “hot-spots” for multimedia communication, MIMO measurements are captured mainly indoors or in microcellular environment. But the high data-rate offered by MIMO systems is also of interest for vehicular traffic, “mobile multimedia”. Therefore, this contribution reports about new MIMO channel measurements in an extraordinarily dynamic scenario, namely a race-track in Austria [6]. While the complexity of MIMO measurements itself is enormous, recording time is crucial here as well. This calls for physical arrays at both link-ends and data post-processing.

The paper is organized as follows: Section 2 will introduce the measurement environment, and Section 3 the channel sounder together with the used antennas and multiplexing. Section 4 will explain the data evaluation involved to arrive at directions-of-arrival (DoAs) and directions-of-departure (DoDs). In Section 5 we will state our measurement results before finally drawing the conclusions in Section 6.

2. Measurement Environment

It is not easy to study MIMO propagation in a realistic environment but still under controllable circumstances. We found a racing track that could be closed to the public for the purpose of our measurements at Salzburgring [6] located near Thalgau in Salzburg, Austria. The rainy weather, however, limited the speed of our (commercial) BMW to at most 180km/h.

During the measurements, the transmitting part of the channel sounder was mounted in the car and the transmit antenna on top of it while driving at high speed. Fig. 1 gives an impression of the measurement situation.

The receiver was located close to the track, at such positions along the circuit where high vehicular speeds had to be expected. A top-view of the racing track gives Figure 2.

Figure 1: *Measurement scenario with the receiving antenna in the fore-ground (Photo by Siemens).*

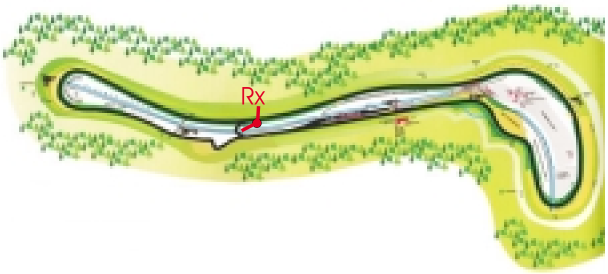

Figure 2: *Salzburgring racing track.*

3. Channel Sounder

The measurements were done with the MIMO capable wideband vector channel sounder RUSK-ATM, manufactured by MEDAV [12]. The sounder was specifically adapted to operate at a center frequency of 2GHz. The transmitted signal is generated in frequency domain to ensure a pre-defined spectrum over 120 MHz bandwidth, and approximately a constant envelope over time. In the receiver the input signal is correlated with the transmitted pulse-shape in the frequency domain resulting in the specific transfer functions. Back-to-back calibration before each measurement ensured an un-biased estimate. Also, transmitter and receiver had to be synchronised via Rubidium clocks at either end for accurate frequency synchronism and a defined time-reference.

For studies on MIMO systems, the double-directional nature of the channel must be exploited. Therefore two simultaneously multiplexed antenna arrays have been used at transmitter and receiver. At the mobile station, it is devised to cover the whole azimuthal range. Therefore, a uniform circular array was developed by Fa. Krenn [13]. It is made of 15 monopoles mounted on a ground plane and was placed on top of the car. The elements were spaced at 0.43λ ($= 6.45$ cm) resulting in a diameter of around 30cm in the middle of the 90cm ground-plane.

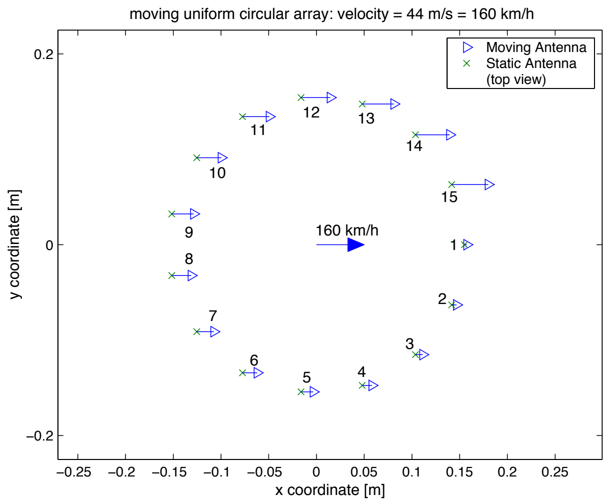

Figure 3: *Deformation of the circular array to the effective spiral geometry.*

The receiver was connected to a fixed uniform linear array from T-NOVA, Germany. The antenna is made of eight patch elements spaced at a distance of $\lambda/2$ ($=$ 7.5 cm). During the measurements, care was taken that the 120^o azimuthal beam-width covered the movement of the mobile transmitter.

With above arrangement, two consecutive sets of $15{\times}8$ pairs of transfer functions, cross-multiplexed in time, were measured every quarter of a second. The temporal displacement of the two sets was limited by the acquisition time of the sounder to a minimum of $3.2\,\mu$s.

When using time-multiplexing of antenna elements in combination with high vehicular speeds, considerations about the true element positions at each multiplexed snap-shot are in order. In our case, the high velocity of the car induced a deformation of the effective antenna array shape at the transmitting side. While the multiplexing delay between receiver element branches is negligible (48μs), it is not for the transmitter side (864μs). During a time-multiplexed measurement frame, the circular array moves a distance of approximately $0.26\lambda \approx 3.8$cm which cannot be neglected in the evaluation. The moving circular array (which was originally not designed for high-speed measurements) becomes an effective array with elements positioned in a spiral geometry! The physical circular array itself (marked by '$\times$') and the effective spiral geometry due to the movement (marked by '$\triangleright$') are shown in Fig. 3.

The overall measurement setup is depicted in Fig. 4.

4. Estimation of DoAs and DoDs

The DoA and DoD are estimated by a Conditional Maximum-Likelihood Estimator (CMLE). This choice is

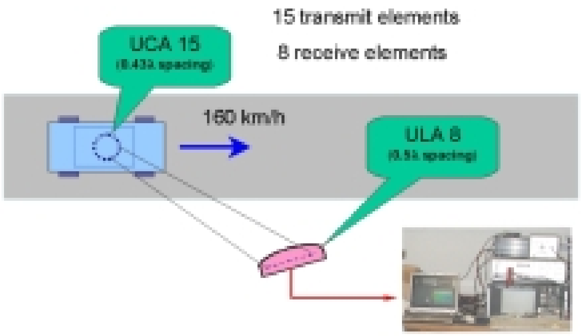

Figure 4: *MIMO channel measurement setup.*

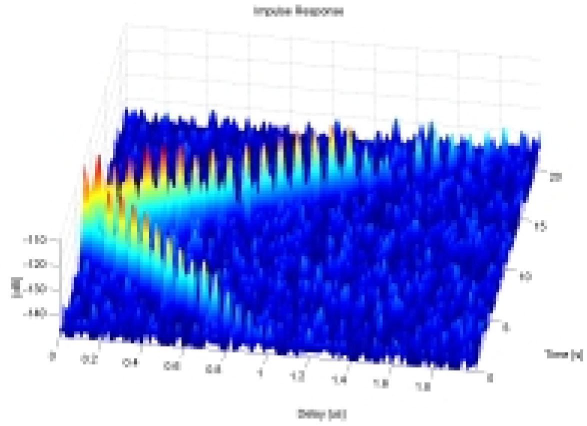

Figure 5: *Time-variant channel impulse response with by-passing car.*

motivated by the effective spiral geometry of the moving uniform circular array. Numerically efficient estimators are not known to the authors for such a geometry. Therefore, an estimation algorithm is selected which can cope with arbitrary element positions. The CMLE is one of the simplest to implement and has considerably lower numerical complexity than the Maximum-Likelihood Estimator (MLE) for several wavefronts carrying stochastic signals. For further details, we refer to [16].

Let $\mathbf{H}_k$ be the observed channel transfer matrices for several snapshots $k = 1 \ldots K$ at a selected delay-bin τ. Further, the transmitter– and receiver–side covariance matrices are estimated via the usual sample-average

$$\hat{\mathbf{C}}_R = \frac{1}{K}\sum_{k=1}^{K}\mathbf{H}_k\mathbf{H}_k^H, \qquad (1)$$

$$\hat{\mathbf{C}}_T = \frac{1}{K}\sum_{k=1}^{K}(\mathbf{H}_k^H\mathbf{H}_k)^* \,. \qquad (2)$$

Let $\mathbf{d}_T(\phi_T)$ and $\mathbf{d}_R(\phi_R)$ denote the steering vectors of the transmitter– and receiver–side, respectively, where ϕ_T is the DoD and ϕ_R is the DoA. These steering vectors span the signal spaces on both sides of the multiple-input, multiple-out mobile radio channel. Let the projection matrices of the associated signal spaces be denoted by $\mathbf{P}_T(\theta_T)$ and $\mathbf{P}_R(\theta_R)$. Here, we have defined the DoD parameter vector θ_T of dimension S which contains the S distinct DoDs, and analogously for the DoAs in θ_R.

Finally, the conditional log-likelihood functions for the DoD and DoA can be formulated as

$$L(\theta_{\mathbf{T}}) = -\log\operatorname{tr}(\mathbf{P}_T^{\perp}(\theta_T)\hat{\mathbf{C}}_T), \qquad (3)$$

$$L(\theta_{\mathbf{R}}) = -\log\operatorname{tr}(\mathbf{P}_R^{\perp}(\theta_R)\hat{\mathbf{C}}_R). \qquad (4)$$

where $(\cdot)^{\perp}$ denotes the orthogonal complement,

$$\mathbf{P}_T^{\perp}(\theta_T) = \mathbf{I} - \mathbf{P}_T(\theta_T)\,. \qquad (5)$$

These goal functions can be maximized in an iterative way: This is explained in the following for the DoD. First, we assume that only one path is present: We do a global search over all ϕ_T. Secondly, we project this estimated signal into the noise space by calculating

$$\tilde{\mathbf{C}}_T = \mathbf{P}_T^{\perp}(\theta_T)\hat{\mathbf{C}}_T\mathbf{P}_T^{\perp}(\theta_T)\,, \qquad (6)$$

In a next step, a global search over all ϕ_T is conducted again under the hypothesis that exactly two paths are present. Having obtained two DoDs. Having obtained two DoD estimates for these two paths by independent global search runs, we need to refine these by a subsequent *joint* optimization. Here, it suffices to use a few steps of a local optimization procedure. For the purposes of this paper, we used the Broyden-Fletcher-Goldfarb-Shanno algorithm [17] .

5. Measurement Results

The result of the data evaluation is for each measurement position the principal delay, and by the conditional maximum likelihood method also the occuring DoAs and DoDs to every such position.

Figure 5 shows the time-variant channel impulse response while the car by-passed the receiver. Obviously, after nearly eight seconds the car is passing the receiver. This is confirmed by the principal delay-peak in the impulse response, which reaches its ultimate position exactly at this instant of time. The whole sampling duration of this measurement is 22 seconds resulting in 76 MIMO snapshots.

For the DoA and DoD estimation we assume three dominant paths. This choice is motivated by the eigenvalues of the covariance matrix $\hat{C}_R$ which constitute three dominant (principal) components. Figure 6 shows the eigenvalues with the car facing the receiver and Fig. 7

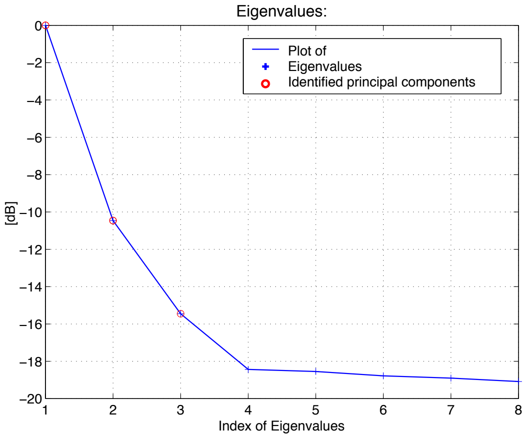

Figure 6: *Eigenvalues of the covariance matrix $\hat{C}_R$ in case of LOS.*

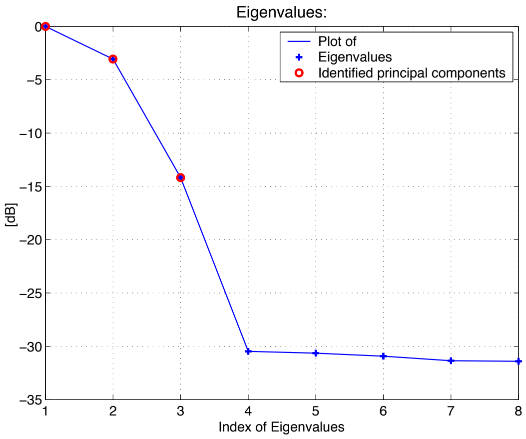

Figure 7: *Eigenvalues of the covariance matrix $\hat{C}_R$ after the car has bypassed the receiver.*

with the car back-sides. In front of the car, one component is the LOS path, and we think the other two components to result from the guard rails on both sides along the track. In the situation after the car passing the receiver, the LOS component is not visible anymore for the receiving antenna. The number of paths, however, has remained three, being more equally powered.

Based on these three components, our maximum likelihood algorithm evaluated the DoAs and DoDs depicted in Figure 8.

In sub-plot a) the delay of the LOS component is plotted over the measurement time. In combination with sub-plot b), where the DoAs are shown over the same grid, the position of the mobile can be tracked. (Let us note in passing that in the opposite link-direction, the DoDs could be used together with the delay-information to position the mobile on-board of the vehicle.) Sub-plot c) finally shows the DoDs along the measurement run.

From Fig. 8 we further see that before as well as after

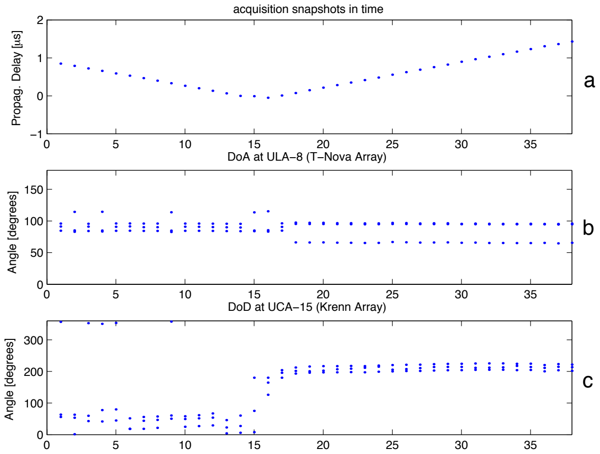

Figure 8: *DoA and DoD Estimation.*

the transition region, the DoAs and DoDs are nearly constant over time, and with low angular spread. (Spatial) Diversity gain is therefore limited; adaptive antennas in such a scenario might primarily serve for link-gain enhancement via beam-forming.

While the DoDs follow the relative orientation of the mobile to the base (receiver) station, this cannot be observed for the DoAs. The reason lies in the fact that the LOS disappears with bypassing of the car. If we could keep hold of the LOS component, we expect the DoAs to change considerably, just like the DoDs. The snapshots with the transmitter close to the receiver (the transition region) show a disconinuity in the estimated DoAs and DoDs being sensitive to the fast changing impulse responses.

6. Conclusions

We have reported new measurements in highly dynamic environments. To assess the double-directional propagation, antenna arrays were used simultaneously at both link ends. The circular array and the time multiplexing motivated the use of a cond. ML approach to compute the DoAs and DoDs for each snapshot. The measurement results in the LOS situation confirm the applicability of the used ML approach, but are yet too few to judge on a complete system's performance.
Three paths have been identified, both in the LOS and NLOS case. These are expected to result from the direct and two specular reflected paths along the track causing a low angular spread of DoAs and DoDs, respectively. In the NLOS case these three paths are further scattered at the scarp in the opposite of the receiver.

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